

# A general non-Markovian master equation for time-dependent Hamiltonians with coupling that is weak, strong, or anything in between

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## I. THE HAMILTONIAN

We start with a time-dependent Hamiltonian of the form:

$$H(t) = H_S(t) + H_I + H_B, \quad (1)$$

$$H_S(t) = \varepsilon_0(t) |0\rangle\langle 0| + \varepsilon_1(t) |1\rangle\langle 1| + V_{10}(t) |1\rangle\langle 0| + V_{01}(t) |0\rangle\langle 1|, \quad (2)$$

$$H_I = |0\rangle\langle 0| \sum_{\mathbf{k}} \left( g_{0\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{0\mathbf{k}}^* b_{\mathbf{k}} \right) + |1\rangle\langle 1| \sum_{\mathbf{k}} \left( g_{1\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{1\mathbf{k}}^* b_{\mathbf{k}} \right), \quad (3)$$

$$H_B = \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}}. \quad (4)$$

For the states  $|0\rangle, |1\rangle$  we have the orthonormal condition:

$$\langle i|j\rangle = \delta_{ij}. \quad (5)$$

## II. UNITARY TRANSFORMATION INTO THE VARIATIONALLY OPTIMIZABLE FRAME

We will apply to  $H(t)$ , the unitary transformation defined by  $e^{\pm V(t)}$  where is the variationally optimizable anti-Hermitian operator:

$$V(t) \equiv |0\rangle\langle 0| \sum_{\mathbf{k}} \left( \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger - \frac{v_{0\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}} \right) + |1\rangle\langle 1| \sum_{\mathbf{k}} \left( \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger - \frac{v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}} \right). \quad (6)$$

in terms of the variational scalar parameters  $v_{i\mathbf{k}}(t)$  defined as:

$$v_{i\mathbf{k}}(t) = \omega_{\mathbf{k}} \alpha_{i\mathbf{k}}(t). \quad (7)$$

which will soon be optimized in order to give the most accurate possible master equation for the system's dynamics in the presence of this bath. We define the following notation for the function (6):

$$\hat{\varphi}_i(t) \equiv \sum_{\mathbf{k}} \left( \frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger - \frac{v_{i\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}} \right), \quad (8)$$

$$V(t) = |0\rangle\langle 0| \hat{\varphi}_0(t) + |1\rangle\langle 1| \hat{\varphi}_1(t). \quad (9)$$

Here  $*$  denotes the complex conjugate. Expanding  $e^{\pm V(t)}$  using the notation (6) will give us the following result:

$$e^{\pm V(t)} = e^{\pm(|0\rangle\langle 0|\hat{\varphi}_0(t) + |1\rangle\langle 1|\hat{\varphi}_1(t))} \quad (10)$$

$$= \mathbb{I} \pm (|0\rangle\langle 0|\hat{\varphi}_0(t) + |1\rangle\langle 1|\hat{\varphi}_1(t)) + \frac{(\pm(|0\rangle\langle 0|\hat{\varphi}_0(t) + |1\rangle\langle 1|\hat{\varphi}_1(t)))^2}{2!} + \dots \quad (11)$$

$$= |0\rangle\langle 0| + |1\rangle\langle 1| \pm (|0\rangle\langle 0|\hat{\varphi}_0(t) + |1\rangle\langle 1|\hat{\varphi}_1(t)) + \frac{|0\rangle\langle 0|\hat{\varphi}_0^2(t)}{2!} + \frac{|1\rangle\langle 1|\hat{\varphi}_1^2(t)}{2!} + \dots \quad (12)$$

$$= |0\rangle\langle 0| \left( \mathbb{I} \pm \hat{\varphi}_0(t) + \frac{\hat{\varphi}_0^2(t)}{2!} \pm \dots \right) + |1\rangle\langle 1| \left( \mathbb{I} \pm \hat{\varphi}_1(t) + \frac{\hat{\varphi}_1^2(t)}{2!} \pm \dots \right) \quad (13)$$

$$= |0\rangle\langle 0|e^{\pm \hat{\varphi}_0(t)} + |1\rangle\langle 1|e^{\pm \hat{\varphi}_1(t)} \quad (14)$$

$$= |0\rangle\langle 0|e^{\pm \sum_{\mathbf{k}} (\alpha_{0\mathbf{k}}(t)b_{\mathbf{k}}^\dagger - \alpha_{0\mathbf{k}}^*(t)b_{\mathbf{k}})} + |1\rangle\langle 1|e^{\pm \sum_{\mathbf{k}} (\alpha_{1\mathbf{k}}(t)b_{\mathbf{k}}^\dagger - \alpha_{1\mathbf{k}}^*(t)b_{\mathbf{k}})} \quad (15)$$

$$= |0\rangle\langle 0|B_0^\pm(t) + |1\rangle\langle 1|B_1^\pm(t), \quad (16)$$

$$B_i^\pm(t) \equiv e^{\pm \sum_{\mathbf{k}} \left( \frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger - \frac{v_{i\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}} \right)}. \quad (17)$$

Let's recall the Zassenhaus formula:

$$e^{r(X+Y)} = e^{rX} e^{rY} e^{-\frac{r^2}{2}[X,Y]} e^{\frac{r^3}{6}(2[Y,[X,Y]] + [X,[X,Y]])} e^{-\frac{r^4}{24}([[[X,Y],X],X] + 3[[[X,Y],X],Y] + 3[[[X,Y],Y],Y])} \dots \quad (18)$$

Since  $\left[ \frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger - \frac{v_{i\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}, \frac{v_{j\mathbf{k}'}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}'}^\dagger - \frac{v_{j\mathbf{k}'}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}'} \right] = 0$  for all  $\mathbf{k}', \mathbf{k}$  and  $i, j$  we can show making  $r = 1$  in (18) the following result:

$$e^{\left( \frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger - \frac{v_{i\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}} \right) + \left( \frac{v_{j\mathbf{k}'}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}'}^\dagger - \frac{v_{j\mathbf{k}'}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}'} \right)} = e^{\frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger - \frac{v_{i\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}} e^{\frac{v_{j\mathbf{k}'}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}'}^\dagger - \frac{v_{j\mathbf{k}'}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}'}} e^{-\frac{1}{2} \left[ \frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger - \frac{v_{i\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}, \frac{v_{j\mathbf{k}'}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}'}^\dagger - \frac{v_{j\mathbf{k}'}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}'} \right]} \dots \quad (19)$$

$$= e^{\frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger - \frac{v_{i\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}} e^{\frac{v_{j\mathbf{k}'}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}'}^\dagger - \frac{v_{j\mathbf{k}'}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}'}} e^{-\frac{1}{2} 0} \dots \quad (20)$$

$$= e^{\frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger - \frac{v_{i\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}} e^{\frac{v_{j\mathbf{k}'}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}'}^\dagger - \frac{v_{j\mathbf{k}'}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}'}}. \quad (21)$$

By induction of this result we can write an expression of  $B_i^\pm(t)$  (shown in equation (17)) as a product of exponentials, which we will call "displacement" operators  $D(\pm v_{i\mathbf{k}}(t))$ :

$$D(\pm v_{i\mathbf{k}}(t)) \equiv e^{\pm \left( \frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger - \frac{v_{i\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}} \right)}, \quad (22)$$

$$B_i^\pm(t) = \prod_{\mathbf{k}} D\left(\pm \frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}}\right). \quad (23)$$

this will help us to write operators  $O(t)$  transformed in the variational frame as:

$$\overline{O(t)} \equiv e^{V(t)} O(t) e^{-V(t)}. \quad (24)$$

We will use the following identities:

$$\overline{|0\chi 0\rangle(t)} = e^{V(t)}|0\chi 0\rangle e^{-V(t)} \quad (25)$$

$$= (|0\chi 0|B_0^+(t) + |1\chi 1|B_1^+(t)) |0\chi 0| (|0\chi 0|B_0^-(t) + |1\chi 1|B_1^-(t)) \quad (26)$$

$$= (|0\chi 0|0\chi 0|B_0^+(t) + |1\chi 1|0\chi 0|B_1^+(t)) (|0\chi 0|B_0^-(t) + |1\chi 1|B_1^-(t)) \quad (27)$$

$$= |0\chi 0|B_0^+(t) (|0\chi 0|B_0^-(t) + |1\chi 1|B_1^-(t)) \quad (28)$$

$$= |0\chi 0|0\chi 0|B_0^+(t) B_0^-(t) + |0\chi 0|1\chi 1|B_0^+(t) B_1^-(t) \quad (29)$$

$$= |0\chi 0|, \quad (30)$$

$$\overline{|1\chi 1\rangle(t)} = (|0\chi 0|B_0^+(t) + |1\chi 1|B_1^+(t)) |1\chi 1| (|0\chi 0|B_0^-(t) + |1\chi 1|B_1^-(t)) \quad (31)$$

$$= (|0\chi 0|1\chi 1|B_0^+(t) + |1\chi 1|1\chi 1|B_1^+(t)) (|0\chi 0|B_0^-(t) + |1\chi 1|B_1^-(t)) \quad (32)$$

$$= |1\chi 1|B_1^+(t) (|0\chi 0|B_0^-(t) + |1\chi 1|B_1^-(t)) \quad (33)$$

$$= |1\chi 1|0\chi 0|B_1^+(t) B_0^-(t) + B_1^+(t) |1\chi 1|1\chi 1|B_1^-(t) \quad (34)$$

$$= B_1^+(t) |1\chi 1|1\chi 1|B_1^-(t) \quad (35)$$

$$= |1\chi 1|, \quad (36)$$

$$\overline{|0\chi 1\rangle(t)} = e^{V(t)}|0\chi 1\rangle e^{-V(t)} \quad (37)$$

$$= (|0\chi 0|B_0^+(t) + |1\chi 1|B_1^+(t)) |0\chi 1| (|0\chi 0|B_0^-(t) + |1\chi 1|B_1^-(t)) \quad (38)$$

$$= (|0\chi 0|0\chi 1|B_0^+(t) + |1\chi 1|B_1^+(t) |0\chi 1|) (|0\chi 0|B_0^-(t) + |1\chi 1|B_1^-(t)) \quad (39)$$

$$= (|0\chi 0|0\chi 1|B_0^+(t) + |1\chi 1|0\chi 1|B_1^+(t)) (|0\chi 0|B_0^-(t) + |1\chi 1|B_1^-(t)) \quad (40)$$

$$= |0\chi 1|B_0^+(t) (|0\chi 0|B_0^-(t) + |1\chi 1|B_1^-(t)) \quad (41)$$

$$= |0\chi 1|0\chi 0|B_0^+(t) B_0^-(t) + |0\chi 1|1\chi 1|B_0^+(t) B_1^-(t) \quad (42)$$

$$= |0\chi 1|B_0^+(t) B_1^-(t), \quad (43)$$

$$\overline{|1\chi 0\rangle(t)} = e^{V(t)}|1\chi 0\rangle e^{-V(t)} \quad (44)$$

$$= (|0\chi 0|B_0^+(t) + |1\chi 1|B_1^+(t)) |1\chi 0| (|0\chi 0|B_0^-(t) + |1\chi 1|B_1^-(t)) \quad (45)$$

$$= (|0\chi 0|1\chi 0|B_0^+(t) + |1\chi 1|B_1^+(t) |1\chi 0|) (|0\chi 0|B_0^-(t) + |1\chi 1|B_1^-(t)) \quad (46)$$

$$= (|0\chi 0|1\chi 0|B_0^+(t) + |1\chi 1|1\chi 0|B_1^+(t)) (|0\chi 0|B_0^-(t) + |1\chi 1|B_1^-(t)) \quad (47)$$

$$= |1\chi 0|B_1^+(t) (|0\chi 0|B_0^-(t) + |1\chi 1|B_1^-(t)) \quad (48)$$

$$= |1\chi 0|0\chi 0|B_1^+(t) B_0^-(t) + |1\chi 0|1\chi 1|B_1^+(t) B_1^-(t) \quad (49)$$

$$= |1\chi 0|B_1^+(t) B_0^-(t), \quad (50)$$

$$\overline{b_{\mathbf{k}}(t)} = e^{V(t)}b_{\mathbf{k}}e^{-V(t)} \quad (51)$$

$$= (|0\chi 0|B_0^+(t) + |1\chi 1|B_1^+(t)) b_{\mathbf{k}} (|0\chi 0|B_0^-(t) + |1\chi 1|B_1^-(t)) \quad (52)$$

$$= |0\chi 0|B_0^+(t)b_{\mathbf{k}}B_0^-(t)|0\chi 0| + |0\chi 0|B_0^+(t)b_{\mathbf{k}}|1\chi 1|B_1^-(t) + |1\chi 1|B_1^+(t)b_{\mathbf{k}}|0\chi 0|B_0^-(t) + |1\chi 1|B_1^+(t)b_{\mathbf{k}}B_1^-(t)|1\chi 1| \quad (53)$$

$$= |0\chi 0|0\chi 0|B_0^+(t)b_{\mathbf{k}}B_0^-(t) + |0\chi 0|1\chi 1|B_0^+(t)b_{\mathbf{k}}B_1^-(t) + |1\chi 1|0\chi 0|B_1^+(t)b_{\mathbf{k}}B_0^-(t) + |1\chi 1|B_1^+(t)b_{\mathbf{k}}B_1^-(t) \quad (54)$$

$$= |0\chi 0| \left( b_{\mathbf{k}} - \frac{v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right) + |1\chi 1| \left( b_{\mathbf{k}} - \frac{v_{1\mathbf{k}}}{\omega_{\mathbf{k}}} \right) \quad (55)$$

$$= (|0\chi 0| + |1\chi 1|) b_{\mathbf{k}} - |1\chi 1| \frac{v_{1\mathbf{k}}}{\omega_{\mathbf{k}}} - |0\chi 0| \frac{v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \quad (56)$$

$$= b_{\mathbf{k}} - |1\chi 1| \frac{v_{1\mathbf{k}}}{\omega_{\mathbf{k}}} - |0\chi 0| \frac{v_{0\mathbf{k}}}{\omega_{\mathbf{k}}}, \quad (57)$$

$$\overline{b_{\mathbf{k}}(t)}^\dagger = e^{V(t)}b_{\mathbf{k}}^\dagger e^{-V(t)} \quad (58)$$

$$= (|0\chi 0|B_0^+(t) + |1\chi 1|B_1^+(t)) b_{\mathbf{k}}^\dagger (|0\chi 0|B_0^-(t) + |1\chi 1|B_1^-(t)) \quad (59)$$

$$= |0\chi 0|B_0^+(t)b_{\mathbf{k}}^\dagger B_0^-(t)|0\chi 0| + |0\chi 0|B_0^+(t)b_{\mathbf{k}}^\dagger |1\chi 1|B_1^-(t) + |1\chi 1|B_1^+(t)b_{\mathbf{k}}^\dagger |0\chi 0|B_0^-(t) + |1\chi 1|B_1^+(t)b_{\mathbf{k}}^\dagger B_1^-(t)|1\chi 1| \quad (60)$$

$$= |0\chi 0|0\chi 0|B_0^+(t)b_{\mathbf{k}}^\dagger B_0^-(t) + |0\chi 0|1\chi 1|B_0^+(t)b_{\mathbf{k}}^\dagger B_1^-(t) + |1\chi 1|0\chi 0|B_1^+(t)b_{\mathbf{k}}^\dagger B_0^-(t) + |1\chi 1|1\chi 1|B_1^+(t)b_{\mathbf{k}}^\dagger B_1^-(t) \quad (61)$$

$$= |0\chi 0| \left( b_{\mathbf{k}}^\dagger - \frac{v_{0\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} \right) + |1\chi 1| \left( b_{\mathbf{k}}^\dagger - \frac{v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} \right) \quad (62)$$

$$= b_{\mathbf{k}}^\dagger - |1\chi 1| \frac{v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} - |0\chi 0| \frac{v_{0\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}}. \quad (63)$$

We have used the following results as well to obtain the transformed  $b_{\mathbf{k}}$  and  $b_{\mathbf{k}}^\dagger$ :

$$B_i^+(t) b_{\mathbf{k}} B_i^-(t) = b_{\mathbf{k}} - \frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}}, \quad (64)$$

$$B_i^+(t) b_{\mathbf{k}}^\dagger B_i^-(t) = b_{\mathbf{k}}^\dagger - \frac{v_{i\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}}. \quad (65)$$

We therefore have the following relationships:

$$\overline{\varepsilon_0(t) |0\rangle\langle 0|} = \varepsilon_0(t) |0\rangle\langle 0|, \quad (66)$$

$$\overline{\varepsilon_1(t) |1\rangle\langle 1|} = \varepsilon_1(t) |1\rangle\langle 1|, \quad (67)$$

$$\overline{V_{10}(t) |1\rangle\langle 0|} = V_{10}(t) |1\rangle\langle 0| B_1^+(t) B_0^-(t), \quad (68)$$

$$\overline{V_{01}(t) |0\rangle\langle 1|} = V_{01}(t) |0\rangle\langle 1| B_0^+(t) B_1^-(t), \quad (69)$$

$$\overline{(g_{i\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{i\mathbf{k}}^* b_{\mathbf{k}})(t)} = g_{i\mathbf{k}} \left( |0\rangle\langle 0| \left( b_{\mathbf{k}}^\dagger - \frac{v_{0\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} \right) + |1\rangle\langle 1| \left( b_{\mathbf{k}}^\dagger - \frac{v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} \right) \right) + g_{i\mathbf{k}}^* \left( |0\rangle\langle 0| \left( b_{\mathbf{k}} - \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) + |1\rangle\langle 1| \left( b_{\mathbf{k}} - \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) \right) \quad (70)$$

$$= g_{i\mathbf{k}} \left( (|0\rangle\langle 0| + |1\rangle\langle 1|) b_{\mathbf{k}}^\dagger - \frac{v_{i\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} |1\rangle\langle 1| - \frac{v_{0\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} |0\rangle\langle 0| \right) + g_{i\mathbf{k}}^* \left( (|0\rangle\langle 0| + |1\rangle\langle 1|) b_{\mathbf{k}} - \frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}} |1\rangle\langle 1| - \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} |0\rangle\langle 0| \right) \quad (71)$$

$$= g_{i\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{i\mathbf{k}}^* b_{\mathbf{k}} - g_{i\mathbf{k}} \frac{v_{0\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} |0\rangle\langle 0| - g_{i\mathbf{k}}^* \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} |0\rangle\langle 0| - g_{i\mathbf{k}} \frac{v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} |1\rangle\langle 1| - g_{i\mathbf{k}}^* \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} |1\rangle\langle 1| \quad (72)$$

$$= g_{i\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{i\mathbf{k}}^* b_{\mathbf{k}} - \left( g_{i\mathbf{k}} \frac{v_{0\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} + g_{i\mathbf{k}}^* \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) |0\rangle\langle 0| - \left( g_{i\mathbf{k}} \frac{v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} + g_{i\mathbf{k}}^* \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) |1\rangle\langle 1|, \quad (73)$$

$$\overline{|0\rangle\langle 0| (g_{0\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{0\mathbf{k}}^* b_{\mathbf{k}})(t)} = (|0\rangle\langle 0| B_0^+(t) + |1\rangle\langle 1| B_1^+(t)) |0\rangle\langle 0| (g_{0\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{0\mathbf{k}}^* b_{\mathbf{k}}) (|0\rangle\langle 0| B_0^-(t) + |1\rangle\langle 1| B_1^-(t)) \quad (74)$$

$$= |0\rangle\langle 0| B_0^+(t) |0\rangle\langle 0| (g_{0\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{0\mathbf{k}}^* b_{\mathbf{k}}) |0\rangle\langle 0| B_0^-(t) \quad (75)$$

$$= |0\rangle\langle 0| B_0^+(t) (g_{0\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{0\mathbf{k}}^* b_{\mathbf{k}}) B_0^-(t) \quad (76)$$

$$= |0\rangle\langle 0| \left( g_{0\mathbf{k}} \left( b_{\mathbf{k}}^\dagger - \frac{v_{0\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} \right) + g_{0\mathbf{k}}^* \left( b_{\mathbf{k}} - \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) \right), \quad (77)$$

$$\overline{|1\rangle\langle 1| (g_{1\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{1\mathbf{k}}^* b_{\mathbf{k}})(t)} = (|0\rangle\langle 0| B_0^+(t) + |1\rangle\langle 1| B_1^+(t)) |1\rangle\langle 1| (g_{1\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{1\mathbf{k}}^* b_{\mathbf{k}}) (|0\rangle\langle 0| B_0^-(t) + |1\rangle\langle 1| B_1^-(t)) \quad (78)$$

$$= |1\rangle\langle 1| B_1^+(t) |1\rangle\langle 1| (g_{1\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{1\mathbf{k}}^* b_{\mathbf{k}}) |1\rangle\langle 1| B_1^-(t) \quad (79)$$

$$= |1\rangle\langle 1| B_1^+(t) (g_{1\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{1\mathbf{k}}^* b_{\mathbf{k}}) B_1^-(t) \quad (80)$$

$$= |1\rangle\langle 1| \left( g_{1\mathbf{k}} \left( b_{\mathbf{k}}^\dagger - \frac{v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} \right) + g_{1\mathbf{k}}^* \left( b_{\mathbf{k}} - \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) \right), \quad (81)$$

$$\overline{\omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}}(t)} = \omega_{\mathbf{k}} (|0\rangle\langle 0| B_0^+(t) + |1\rangle\langle 1| B_1^+(t)) b_{\mathbf{k}}^\dagger b_{\mathbf{k}} (|0\rangle\langle 0| B_0^-(t) + |1\rangle\langle 1| B_1^-(t)) \quad (82)$$

$$= \omega_{\mathbf{k}} (|0\rangle\langle 0| \Pi_{\mathbf{k}'} D\left(\frac{v_{0\mathbf{k}'}(t)}{\omega_{\mathbf{k}'}}\right) + |1\rangle\langle 1| \Pi_{\mathbf{k}'} D\left(\frac{v_{1\mathbf{k}'}(t)}{\omega_{\mathbf{k}'}}\right)) b_{\mathbf{k}}^\dagger b_{\mathbf{k}} (|0\rangle\langle 0| \Pi_{\mathbf{k}'} D\left(-\frac{v_{0\mathbf{k}'}(t)}{\omega_{\mathbf{k}'}}\right) + |1\rangle\langle 1| \Pi_{\mathbf{k}'} D\left(-\frac{v_{1\mathbf{k}'}(t)}{\omega_{\mathbf{k}'}}\right)) \quad (83)$$

$$= \omega_{\mathbf{k}} (|0\rangle\langle 0| B_0^+(t) b_{\mathbf{k}}^\dagger b_{\mathbf{k}} B_0^-(t) + |1\rangle\langle 1| B_1^+(t) b_{\mathbf{k}}^\dagger b_{\mathbf{k}} B_1^-(t)) \quad (84)$$

$$= \omega_{\mathbf{k}} \left( |0\rangle\langle 0| D\left(\frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}}\right) b_{\mathbf{k}}^\dagger b_{\mathbf{k}} D\left(-\frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}}\right) \prod_{\mathbf{k}' \neq \mathbf{k}} \left( D\left(\frac{v_{0\mathbf{k}'}(t)}{\omega_{\mathbf{k}'}}\right) D\left(-\frac{v_{0\mathbf{k}'}(t)}{\omega_{\mathbf{k}'}}\right) \right) \right. \quad (85)$$

$$\left. + |1\rangle\langle 1| D\left(\frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}}\right) b_{\mathbf{k}}^\dagger b_{\mathbf{k}} D\left(-\frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}}\right) \prod_{\mathbf{k}' \neq \mathbf{k}} \left( D\left(\frac{v_{1\mathbf{k}'}(t)}{\omega_{\mathbf{k}'}}\right) D\left(-\frac{v_{1\mathbf{k}'}(t)}{\omega_{\mathbf{k}'}}\right) \right) \right) \quad (86)$$

$$= \omega_{\mathbf{k}} \left( |0\rangle\langle 0| D \left( \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) b_{\mathbf{k}}^\dagger b_{\mathbf{k}} D \left( -\frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) \mathbb{I} + |1\rangle\langle 1| D \left( \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) b_{\mathbf{k}}^\dagger b_{\mathbf{k}} D \left( -\frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) \mathbb{I} \right) \quad (87)$$

$$= \omega_{\mathbf{k}} \left( |0\rangle\langle 0| \left( b_{\mathbf{k}}^\dagger - \frac{v_{0\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} \right) \left( b_{\mathbf{k}} - \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) + |1\rangle\langle 1| \left( b_{\mathbf{k}}^\dagger - \frac{v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} \right) \left( b_{\mathbf{k}} - \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) \right) \quad (88)$$

$$= \omega_{\mathbf{k}} \left( |0\rangle\langle 0| \left( b_{\mathbf{k}}^\dagger b_{\mathbf{k}} - \frac{v_{0\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}} - \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger + \left| \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 \right) + |1\rangle\langle 1| \left( b_{\mathbf{k}}^\dagger b_{\mathbf{k}} - \frac{v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}} - \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger + \left| \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 \right) \right) \quad (89)$$

$$= \omega_{\mathbf{k}} \left( |0\rangle\langle 0| b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + |1\rangle\langle 1| b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + |1\rangle\langle 1| \left( \left| \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 - \frac{v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}} - \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger \right) + |0\rangle\langle 0| \left( \left| \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 - \frac{v_{0\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}} - \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger \right) \right) \quad (90)$$

$$= \omega_{\mathbf{k}} \left( b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + |1\rangle\langle 1| \left( \left| \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 - \frac{v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}} - \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger \right) + |0\rangle\langle 0| \left( \left| \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 - \frac{v_{0\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}} - \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger \right) \right) \quad (91)$$

$$= \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + \omega_{\mathbf{k}} \left( |1\rangle\langle 1| \left( \left| \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 - \frac{v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}} - \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger \right) + |0\rangle\langle 0| \left( \left| \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 - \frac{v_{0\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}} - \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger \right) \right) \quad (92)$$

$$= \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + |1\rangle\langle 1| \left( \frac{|v_{1\mathbf{k}}(t)|^2}{\omega_{\mathbf{k}}} - v_{1\mathbf{k}}^*(t) b_{\mathbf{k}} - v_{1\mathbf{k}}(t) b_{\mathbf{k}}^\dagger \right) + |0\rangle\langle 0| \left( \frac{|v_{0\mathbf{k}}(t)|^2}{\omega_{\mathbf{k}}} - v_{0\mathbf{k}}^*(t) b_{\mathbf{k}} - v_{0\mathbf{k}}(t) b_{\mathbf{k}}^\dagger \right) \quad (93)$$

$$= \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + |1\rangle\langle 1| \left( \frac{|v_{1\mathbf{k}}(t)|^2}{\omega_{\mathbf{k}}} - \left( v_{1\mathbf{k}}^*(t) b_{\mathbf{k}} + v_{1\mathbf{k}}(t) b_{\mathbf{k}}^\dagger \right) \right) + |0\rangle\langle 0| \left( \frac{|v_{0\mathbf{k}}(t)|^2}{\omega_{\mathbf{k}}} - \left( v_{0\mathbf{k}}^*(t) b_{\mathbf{k}} + v_{0\mathbf{k}}(t) b_{\mathbf{k}}^\dagger \right) \right). \quad (94)$$

So all parts of  $H(t)$  can be written in the variationally optimizable frame now:

$$\overline{H_S(t)} = \overline{\varepsilon_0(t) |0\rangle\langle 0|} + \overline{\varepsilon_1(t) |1\rangle\langle 1|} + \overline{V_{10}(t) |1\rangle\langle 0|} + \overline{V_{01}(t) |0\rangle\langle 1|} \quad (95)$$

$$= \varepsilon_0(t) |0\rangle\langle 0| + \varepsilon_1(t) |1\rangle\langle 1| + V_{10}(t) |1\rangle\langle 0| B_1^+(t) B_0^-(t) + V_{01}(t) |0\rangle\langle 1| B_0^+(t) B_1^-(t), \quad (96)$$

$$\overline{H_I} = \sum_{\mathbf{k}} |0\rangle\langle 0| \left( g_{0\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{0\mathbf{k}}^* b_{\mathbf{k}} \right) + \sum_{\mathbf{k}} |1\rangle\langle 1| \left( g_{1\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{1\mathbf{k}}^* b_{\mathbf{k}} \right) \quad (97)$$

$$= \sum_{\mathbf{k}} |0\rangle\langle 0| \left( g_{0\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{0\mathbf{k}}^* b_{\mathbf{k}} \right) + \sum_{\mathbf{k}} |1\rangle\langle 1| \left( g_{1\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{1\mathbf{k}}^* b_{\mathbf{k}} \right) \quad (98)$$

$$= \sum_{\mathbf{k}} |0\rangle\langle 0| \left( g_{0\mathbf{k}} \left( b_{\mathbf{k}}^\dagger - \frac{v_{0\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} \right) + g_{0\mathbf{k}}^* \left( b_{\mathbf{k}} - \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) \right) + \sum_{\mathbf{k}} |1\rangle\langle 1| \left( g_{1\mathbf{k}} \left( b_{\mathbf{k}}^\dagger - \frac{v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} \right) + g_{1\mathbf{k}}^* \left( b_{\mathbf{k}} - \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) \right) \quad (99)$$

$$= \sum_{\mathbf{k}} |0\rangle\langle 0| \left( g_{0\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{0\mathbf{k}}^* b_{\mathbf{k}} \right) + \sum_{\mathbf{k}} |1\rangle\langle 1| \left( g_{1\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{1\mathbf{k}}^* b_{\mathbf{k}} \right) - \sum_{\mathbf{k}} |0\rangle\langle 0| \left( g_{0\mathbf{k}} \frac{v_{0\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} + g_{0\mathbf{k}}^* \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) - \sum_{\mathbf{k}} |1\rangle\langle 1| \left( g_{1\mathbf{k}} \frac{v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} + g_{1\mathbf{k}}^* \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right), \quad (100)$$

$$\overline{H_B} = \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} \quad (101)$$

$$= \sum_{\mathbf{k}} \left( \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + |1\rangle\langle 1| \left( \frac{|v_{1\mathbf{k}}(t)|^2}{\omega_{\mathbf{k}}} - \left( v_{1\mathbf{k}}^*(t) b_{\mathbf{k}} + v_{1\mathbf{k}}(t) b_{\mathbf{k}}^\dagger \right) \right) + |0\rangle\langle 0| \left( \frac{|v_{0\mathbf{k}}(t)|^2}{\omega_{\mathbf{k}}} - \left( v_{0\mathbf{k}}^*(t) b_{\mathbf{k}} + v_{0\mathbf{k}}(t) b_{\mathbf{k}}^\dagger \right) \right) \right) \quad (102)$$

$$= \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + \sum_{\mathbf{k}} \left( |1\rangle\langle 1| \left( \frac{|v_{1\mathbf{k}}(t)|^2}{\omega_{\mathbf{k}}} - \left( v_{1\mathbf{k}}^*(t) b_{\mathbf{k}} + v_{1\mathbf{k}}(t) b_{\mathbf{k}}^\dagger \right) \right) + |0\rangle\langle 0| \left( \frac{|v_{0\mathbf{k}}(t)|^2}{\omega_{\mathbf{k}}} - \left( v_{0\mathbf{k}}^*(t) b_{\mathbf{k}} + v_{0\mathbf{k}}(t) b_{\mathbf{k}}^\dagger \right) \right) \right). \quad (103)$$

Finally merging these expressions gives the transformed Hamiltonian:

$$\overline{H(t)} = \sum_j \varepsilon_j(t) |j\rangle\langle j| + \sum_{j \neq j'} V_{jj'}(t) |j\rangle\langle j'| B_j^+(t) B_{j'}^-(t) + \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + \sum_{j\mathbf{k}} |j\rangle\langle j| \left( (g_{j\mathbf{k}} - v_{j\mathbf{k}}(t)) b_{\mathbf{k}}^\dagger + (g_{j\mathbf{k}} - v_{j\mathbf{k}}(t))^* b_{\mathbf{k}} + \frac{|v_{j\mathbf{k}}(t)|^2}{\omega_{\mathbf{k}}} - \left( g_{j\mathbf{k}} \frac{v_{j\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} + g_{j\mathbf{k}}^* \frac{v_{j\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) \right). \quad (104)$$



So the product of the matrix representation of  $b^\dagger$  and  $b$  with  $-\beta$  is:

$$-\beta\omega b^\dagger b = -\beta\omega \begin{pmatrix} 0 & 0 & 0 & \dots & 0 & \dots \\ 0 & 1 & 0 & \dots & 0 & \dots \\ 0 & 0 & 2 & \dots & 0 & \dots \\ \vdots & \vdots & \vdots & \ddots & \vdots & \dots \\ 0 & 0 & 0 & \dots & n & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \quad (115)$$

$$= \sum_{j=0}^{\infty} -j\beta\omega |j\rangle\langle j|, \quad (116)$$

So the density matrix  $\rho_B$  written in the coherence representation can be obtained using the Zassenhaus formula and the fact that  $[|j\rangle\langle j|, |i\rangle\langle i|] = 0$  for all  $i, j$ .

$$\exp\left(-\beta\omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}}\right) = \sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}}\beta\omega_{\mathbf{k}}) |j_{\mathbf{k}}\rangle\langle j_{\mathbf{k}}|, \quad (117)$$

$$\exp\left(-\beta \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}}\right) = \prod_{\mathbf{k}} \sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}}\beta\omega_{\mathbf{k}}) |j_{\mathbf{k}}\rangle\langle j_{\mathbf{k}}|. \quad (118)$$

The value of  $\text{Tr}\left(\exp\left(-\beta\omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}}\right)\right)$  is:

$$\text{Tr}\left(\exp\left(-\beta\omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}}\right)\right) = \text{Tr}\left(\sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}}\beta\omega_{\mathbf{k}}) |j_{\mathbf{k}}\rangle\langle j_{\mathbf{k}}|\right) \quad (119)$$

$$= \sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}}\beta\omega_{\mathbf{k}}) \quad (120)$$

$$= \sum_{j_{\mathbf{k}}} \exp(-\beta\omega_{\mathbf{k}})^{j_{\mathbf{k}}} \quad (121)$$

$$= \frac{1}{1 - \exp(-\beta\omega_{\mathbf{k}})} \quad (\text{by geometric series}) \quad (122)$$

$$\equiv f_{\text{Bose-Einstein}}(-\beta\omega_{\mathbf{k}}), \quad (123)$$

$$\text{Tr}\left(\exp\left(-\beta \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}}\right)\right) = \text{Tr}\left(\prod_{\mathbf{k}} \sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}}\beta\omega_{\mathbf{k}}) |j_{\mathbf{k}}\rangle\langle j_{\mathbf{k}}|\right) \quad (124)$$

$$= \prod_{\mathbf{k}} \text{Tr}\left(\sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}}\beta\omega_{\mathbf{k}}) |j_{\mathbf{k}}\rangle\langle j_{\mathbf{k}}|\right) \quad (125)$$

$$= \prod_{\mathbf{k}} f_{\text{Bose-Einstein}}(-\beta\omega_{\mathbf{k}}). \quad (126)$$

So the density matrix of the bath is:

$$\rho_B = \frac{e^{-\beta H_B}}{\text{Tr}(e^{-\beta H_B})} \quad (127)$$

$$= \frac{\prod_{\mathbf{k}} \sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}}\beta\omega_{\mathbf{k}}) |j_{\mathbf{k}}\rangle\langle j_{\mathbf{k}}|}{\prod_{\mathbf{k}} f_{\text{Bose-Einstein}}(-\beta\omega_{\mathbf{k}})} \quad (128)$$

$$= \prod_{\mathbf{k}} \frac{\sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}}\beta\omega_{\mathbf{k}}) |j_{\mathbf{k}}\rangle\langle j_{\mathbf{k}}|}{f_{\text{Bose-Einstein}}(-\beta\omega_{\mathbf{k}})}. \quad (129)$$

Now, given that creation and annihilation satisfy:

$$b_{\mathbf{k}} |j_{\mathbf{k}}\rangle = \sqrt{j_{\mathbf{k}}} |j_{\mathbf{k}} - 1\rangle, \quad (130)$$

$$b_{\mathbf{k}}^\dagger |j_{\mathbf{k}}\rangle = \sqrt{j_{\mathbf{k}} + 1} |j_{\mathbf{k}} + 1\rangle. \quad (131)$$

Then we can prove that  $\langle B_{iz} \rangle_{\overline{H_B}} = 0$  using the following property based on (130)-(131):

$$\langle B_{iz}(t) \rangle_{\overline{H_B}} = \text{Tr}(\rho_B B_{iz}(t)) = \text{Tr}(B_{iz}(t) \rho_B) \quad (132)$$

$$= \text{Tr} \left( \left( \sum_{\mathbf{k}} \left( (g_{i\mathbf{k}} - v_{i\mathbf{k}}(t)) b_{\mathbf{k}}^\dagger + (g_{i\mathbf{k}} - v_{i\mathbf{k}}(t))^* b_{\mathbf{k}} \right) \right) \rho_B \right) \quad (133)$$

$$= \sum_{\mathbf{k}} \text{Tr} \left( (g_{i\mathbf{k}} - v_{i\mathbf{k}}(t)) b_{\mathbf{k}}^\dagger \rho_B \right) + \sum_{\mathbf{k}} \text{Tr} \left( (g_{i\mathbf{k}} - v_{i\mathbf{k}}(t))^* b_{\mathbf{k}} \rho_B \right) \quad (134)$$

$$= \sum_{\mathbf{k}} (g_{i\mathbf{k}} - v_{i\mathbf{k}}(t)) \text{Tr} \left( b_{\mathbf{k}}^\dagger \rho_B \right) + \sum_{\mathbf{k}} (g_{i\mathbf{k}} - v_{i\mathbf{k}}(t))^* \text{Tr} \left( b_{\mathbf{k}} \rho_B \right) \quad (135)$$

$$= \sum_{\mathbf{k}} \text{Tr} \left( (g_{i\mathbf{k}} - v_{i\mathbf{k}}(t)) b_{\mathbf{k}}^\dagger \prod_{\mathbf{k}} \frac{\sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}} \beta \omega_{\mathbf{k}}) |j_{\mathbf{k}}\rangle \langle j_{\mathbf{k}}|}{f_{\text{Bose-Einstein}}(-\beta \omega_{\mathbf{k}})} \right) + \sum_{\mathbf{k}} \text{Tr} \left( (g_{i\mathbf{k}} - v_{i\mathbf{k}}(t))^* b_{\mathbf{k}} \prod_{\mathbf{k}} \frac{\sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}} \beta \omega_{\mathbf{k}}) |j_{\mathbf{k}}\rangle \langle j_{\mathbf{k}}|}{f_{\text{Bose-Einstein}}(-\beta \omega_{\mathbf{k}})} \right) \quad (136)$$

$$= \sum_{\mathbf{k}} (g_{i\mathbf{k}} - v_{i\mathbf{k}}(t)) \text{Tr} \left( b_{\mathbf{k}}^\dagger \prod_{\mathbf{k}} \frac{\sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}} \beta \omega_{\mathbf{k}}) |j_{\mathbf{k}}\rangle \langle j_{\mathbf{k}}|}{f_{\text{Bose-Einstein}}(-\beta \omega_{\mathbf{k}})} \right) + \sum_{\mathbf{k}} (g_{i\mathbf{k}} - v_{i\mathbf{k}}(t))^* \text{Tr} \left( b_{\mathbf{k}} \prod_{\mathbf{k}} \frac{\sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}} \beta \omega_{\mathbf{k}}) |j_{\mathbf{k}}\rangle \langle j_{\mathbf{k}}|}{f_{\text{Bose-Einstein}}(-\beta \omega_{\mathbf{k}})} \right), \quad (137)$$

$$\text{Tr} \left( b_{\mathbf{k}}^\dagger \sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}} \beta \omega_{\mathbf{k}}) |j_{\mathbf{k}}\rangle \langle j_{\mathbf{k}}| \right) = \text{Tr} \left( \left( \sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}} \beta \omega_{\mathbf{k}}) \right) b_{\mathbf{k}}^\dagger |j_{\mathbf{k}}\rangle \langle j_{\mathbf{k}}| \right) \quad (\text{by cyclic permutivity of trace, move } b_{\mathbf{k}}^\dagger) \quad (138)$$

$$= \text{Tr} \left( \left( \sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}} \beta \omega_{\mathbf{k}}) \right) \sqrt{j_{\mathbf{k}} + 1} |j_{\mathbf{k}} + 1\rangle \langle j_{\mathbf{k}}| \right) \quad (139)$$

$$= 0, \quad (140)$$

$$\text{Tr} \left( b_{\mathbf{k}} \sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}} \beta \omega_{\mathbf{k}}) |j_{\mathbf{k}}\rangle \langle j_{\mathbf{k}}| \right) = \text{Tr} \left( \left( \sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}} \beta \omega_{\mathbf{k}}) \right) b_{\mathbf{k}} |j_{\mathbf{k}}\rangle \langle j_{\mathbf{k}}| \right) \quad (\text{by cyclic permutivity of trace, move } b_{\mathbf{k}}) \quad (141)$$

$$= \text{Tr} \left( \left( \sum_{j_{\mathbf{k}}} \exp(-j_{\mathbf{k}} \beta \omega_{\mathbf{k}}) \right) \sqrt{j_{\mathbf{k}}} |j_{\mathbf{k}} - 1\rangle \langle j_{\mathbf{k}}| \right) \quad (142)$$

$$= 0. \quad (143)$$

we therefore find that:

$$\langle B_{iz}(t) \rangle_{\overline{H_B}} = 0. \quad (144)$$

Another important expected value is  $B(t) = \langle B^\pm(t) \rangle_{\overline{H_B}}$ , where  $B^\pm(t) = e^{\pm \sum_{\mathbf{k}} \left( \frac{v_{\mathbf{k}}(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger - \frac{v_{\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} b_{\mathbf{k}} \right)}$  is given by:



$$\langle B^\pm \rangle_{H_B} = \text{Tr} (\rho_B B^\pm) = \text{Tr} (B^\pm \rho_B) \quad (145)$$

$$= \text{Tr} \left( e^{\pm \sum_{\mathbf{k}} \left( \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} b_{\mathbf{k}}^\dagger - \frac{v_{\mathbf{k}}^*}{\omega_{\mathbf{k}}} b_{\mathbf{k}} \right)} \rho_B \right) \quad (146)$$

$$= \prod_{\mathbf{k}} \text{Tr} (D(\pm \alpha_{\mathbf{k}}) \rho_B) \quad (147)$$

$$= \prod_{\mathbf{k}} \langle D(\pm \alpha_{\mathbf{k}}) \rangle. \quad (148)$$

Given that we can write a density operator as:

$$\rho = \int P(\alpha) |\alpha\rangle\langle\alpha| d^2\alpha. \quad (149)$$

where  $P(\alpha)$  satisfies  $\int P(\alpha) d^2\alpha = 1$  and describes the state. It follows that the expectation value of an operator  $A$  with respect to the density operator described by  $P(\alpha)$  is given by:

$$\langle A \rangle = \text{Tr} (A\rho) \quad (150)$$

$$= \int P(\alpha) \langle \alpha | A | \alpha \rangle d^2\alpha. \quad (151)$$

We are typically interested in thermal state density operators, for which it can be shown that  $P(\alpha) = \frac{1}{\pi N} \exp\left(-\frac{|\alpha|^2}{N}\right)$  where  $N = (e^{\beta\omega} - 1)^{-1}$  is the average number of excitations in an oscillator of frequency  $\omega$  at inverse temperature  $\beta = 1/k_B T$ .

Using the integral representation (151) we could obtain that the expected value for the displacement operator  $D(h)$  with  $h \in \mathbb{C}$  is equal to:

$$\langle D(h) \rangle = \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha|^2}{N}\right) \langle \alpha | D(h) | \alpha \rangle d^2 \alpha \quad (152)$$

$$= \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha|^2}{N}\right) \langle 0 | D(-\alpha) D(h) D(\alpha) | 0 \rangle d^2 \alpha, \quad (153)$$

$$D(h) D(\alpha) = D(h + \alpha) e^{\frac{1}{2}(h\alpha^* - h^*\alpha)}, \quad (154)$$

$$D(-\alpha) (D(h) D(\alpha)) = D(-\alpha) D(h + \alpha) e^{\frac{1}{2}(h\alpha^* - h^*\alpha)} \quad (155)$$

$$= D(h) e^{\frac{1}{2}(-\alpha(h+\alpha)^* + \alpha^*(h+\alpha))} e^{\frac{1}{2}(h\alpha^* - h^*\alpha)} \quad (156)$$

$$= D(\alpha) e^{\frac{1}{2}(-\alpha h^* - |\alpha|^2 + \alpha^* h + |\alpha|^2)} e^{\frac{1}{2}(h\alpha^* - h^*\alpha)} \quad (157)$$

$$= D(\alpha) e^{(h\alpha^* - h^*\alpha)}, \quad (158)$$

$$\langle D(h) \rangle = \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha|^2}{N}\right) \langle 0 | D(h) \exp(h\alpha^* - h^*\alpha) | 0 \rangle d^2 \alpha \quad (159)$$

$$= \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha|^2}{N}\right) \exp(h\alpha^* - h^*\alpha) \langle 0 | D(h) | 0 \rangle d^2 \alpha \quad (160)$$

$$= \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha|^2}{N}\right) \exp(h\alpha^* - h^*\alpha) \langle 0 | h \rangle d^2 \alpha, \quad (161)$$

$$|\alpha\rangle = \exp\left(-\frac{|\alpha|^2}{2}\right) \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle, \quad (162)$$

$$\langle D(h) \rangle = \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha|^2}{N}\right) \exp(h\alpha^* - h^*\alpha) \langle 0 | \exp\left(-\frac{|h|^2}{2}\right) \sum_{n=0}^{\infty} \frac{h^n}{\sqrt{n!}} |n\rangle d^2 \alpha \quad (163)$$

$$= \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha|^2}{N}\right) \exp(h\alpha^* - h^*\alpha) \exp\left(-\frac{|h|^2}{2}\right) d^2 \alpha \quad (164)$$

$$= \frac{\exp\left(-\frac{|h|^2}{2}\right)}{\pi N} \int \exp\left(-\frac{|\alpha|^2}{N} + h\alpha^* - h^*\alpha\right) d^2 \alpha, \quad (165)$$

$$\alpha = x + iy, \quad (166)$$

$$\langle D(h) \rangle = \frac{\exp\left(-\frac{|h|^2}{2}\right)}{\pi N} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \exp\left(-\frac{x^2 + y^2}{N} + h(x - iy) - h^*(x + iy)\right) dx dy \quad (167)$$

$$= \frac{\exp\left(-\frac{|h|^2}{2}\right)}{\pi N} \int_{-\infty}^{\infty} \exp\left(-\frac{x^2}{N} + hx - h^*x\right) dx \int_{-\infty}^{\infty} \exp\left(-\frac{y^2}{N} - ihy - ih^*y\right) dy, \quad (168)$$

$$-\frac{x^2}{N} + hx - h^*x = -\frac{1}{N} (x^2 - Nhx + Nh^*x) \quad (169)$$

$$= -\frac{1}{N} \left( x + \frac{(Nh^* - Nh)}{2} \right)^2 + \frac{N(h^* - h)^2}{4}, \quad (170)$$

$$\frac{y^2}{N} - ihy - ih^*y = -\frac{1}{N} (y^2 + iNhy + iNh^*y) \quad (171)$$

$$= -\frac{1}{N} \left( y^2 + \frac{iN(h + h^*)}{2} \right) - \frac{N(h + h^*)^2}{4}, \quad (172)$$

$$\langle D(h) \rangle = \frac{\exp\left(-\frac{|h|^2}{2} + \frac{N(h^* - h)^2}{4} - \frac{N(h + h^*)^2}{4}\right)}{\pi N} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \exp\left(-\frac{1}{N} \left( x + \frac{(Nh^* - Nh)}{2} \right)^2 - \frac{1}{N} \left( y^2 + \frac{iN(h + h^*)}{2} \right)\right) dx dy, \quad (173)$$

$$\sqrt{2\pi}\sigma = \int_{-\infty}^{\infty} \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right) dx, \quad (174)$$

$$\langle D(h) \rangle = \frac{\exp\left(-\frac{|h|^2}{2} + \frac{N(h^* - h)^2}{4} - \frac{N(h + h^*)^2}{4}\right)}{\pi N} \int_{-\infty}^{\infty} \exp\left(-\frac{\left(x + \frac{(Nh^* - Nh)}{2}\right)^2}{2\left(\sqrt{\frac{N}{2}}\right)^2}\right) dx \int_{-\infty}^{\infty} \exp\left(-\frac{\left(y^2 + \frac{iN(h + h^*)}{2}\right)}{2\left(\sqrt{\frac{N}{2}}\right)^2}\right) dy \quad (175)$$

$$= \frac{\exp\left(-\frac{|h|^2}{2} + \frac{N(h^* - h)^2}{4} - \frac{N(h + h^*)^2}{4}\right)}{\pi N} \left(\sqrt{2\pi}\sqrt{\frac{N}{2}}\right)^2 \quad (176)$$

$$= \exp\left(-\frac{|h|^2}{2} + \frac{N(h^* - h)^2}{4} - \frac{N(h + h^*)^2}{4}\right) \quad (177)$$

$$= \exp\left(-\frac{|h|^2}{2} + \frac{N(h^{*2} - 2hh^* + h^2) - N(h^2 + 2hh^* + h^{*2})}{4}\right) \quad (178)$$

$$= \exp\left(-|h|^2 \left(N + \frac{1}{2}\right)\right) \quad (179)$$

$$= \exp\left(-|h|^2 \left(\frac{1}{e^{\beta\omega} - 1} + \frac{1}{2}\right)\right) \quad (180)$$

$$= \exp\left(-\frac{|h|^2}{2} \left(\frac{e^{\beta\omega} + 1}{e^{\beta\omega} - 1}\right)\right) \quad (181)$$

$$= \exp\left(-\frac{|h|^2}{2} \coth\left(\frac{\beta\omega}{2}\right)\right). \quad (182)$$

In the last line we used  $\frac{e^{\beta\omega} + 1}{e^{\beta\omega} - 1} = \coth\left(\frac{\beta\omega}{2}\right)$ . So the value of (147) using (182) is given by:

$$B = \exp\left(-\sum_{\mathbf{k}} \frac{|\alpha_{\mathbf{k}}|^2}{2} \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)\right). \quad (183)$$

We will now force  $\langle \overline{H_I} \rangle_{\overline{H_B}} = 0$ . We will also introduce the bath renormalizing driving in  $\overline{H_S}$  to treat it non-perturbatively in the subsequent formalism, we associate the terms related with  $B^+ \sigma^+$  and  $B^- \sigma^-$  with the interaction part of the Hamiltonian  $\overline{H_I}$  and we subtract their expected value in order to satisfy  $\langle \overline{H_I} \rangle_{\overline{H_B}} = 0$ .

A final form of the terms of the Hamiltonian  $\overline{H}$  is:

$$\overline{H(t)} = \sum_j \varepsilon_j(t) |j\rangle\langle j| + \sum_{j \neq j'} V_{jj'}(t) |j\rangle\langle j'| B_j^+(t) B_{j'}^-(t) + \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + \sum_{j\mathbf{k}} |j\rangle\langle j| \left( (g_{j\mathbf{k}} - v_{j\mathbf{k}}(t)) b_{\mathbf{k}}^\dagger + (g_{j\mathbf{k}} - v_{j\mathbf{k}}(t))^* b_{\mathbf{k}} + \frac{|v_{j\mathbf{k}}(t)|^2}{\omega_{\mathbf{k}}} - \left( g_{j\mathbf{k}} \frac{v_{j\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} + g_{j\mathbf{k}}^* \frac{v_{j\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) \right) \quad (184)$$

$$= \sum_j \varepsilon_j(t) |j\rangle\langle j| + \sum_{j \neq j'} V_{jj'}(t) |j\rangle\langle j'| B_{jj'}^+(t) + \sum_j |j\rangle\langle j| B_{jj}^+(t) + \sum_{j \neq j'} V_{jj'}(t) |j\rangle\langle j'| \left( B_j^+(t) B_{j'}^-(t) - B_{jj'}(t) \right) + \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} \quad (185)$$

$$\equiv \overline{H_S(t)} + \overline{H_I} + \overline{H_B}. \quad (186)$$

The parts of the Hamiltonian splitted are obtained using the following expected value:

$$\langle B_i^+(t) B_j^-(t) \rangle = B_{ij}(t) \quad (187)$$

$$= \left\langle \prod_{\mathbf{k}} D\left(\frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}}\right) \prod_{\mathbf{k}} D\left(-\frac{v_{j\mathbf{k}}(t)}{\omega_{\mathbf{k}}}\right) \right\rangle \quad (188)$$

$$= \left\langle \prod_{\mathbf{k}} \left( D\left(\frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}}\right) D\left(-\frac{v_{j\mathbf{k}}(t)}{\omega_{\mathbf{k}}}\right) \right) \right\rangle \quad (189)$$

$$= \left\langle \prod_{\mathbf{k}} \left( D\left(\frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}} - \frac{v_{j\mathbf{k}}(t)}{\omega_{\mathbf{k}}}\right) e^{\frac{1}{2} \left( \frac{v_{i\mathbf{k}}^*(t) v_{j\mathbf{k}}(t) - v_{i\mathbf{k}}(t) v_{j\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}^2} \right)} \right) \right\rangle \quad (190)$$

$$= \prod_{\mathbf{k}} \left\langle D\left(\frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}} - \frac{v_{j\mathbf{k}}(t)}{\omega_{\mathbf{k}}}\right) \right\rangle e^{\frac{1}{2} \left( \frac{v_{i\mathbf{k}}^*(t) v_{j\mathbf{k}}(t) - v_{i\mathbf{k}}(t) v_{j\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}^2} \right)} \quad (191)$$

$$= \prod_{\mathbf{k}} \exp\left(-\frac{1}{2} \left| \frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}} - \frac{v_{j\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)\right) e^{\frac{1}{2} \left( \frac{v_{i\mathbf{k}}^*(t) v_{j\mathbf{k}}(t) - v_{i\mathbf{k}}(t) v_{j\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}^2} \right)} \quad (192)$$

$$= \exp\left(-\frac{1}{2} \sum_{\mathbf{k}} \left| \frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}} - \frac{v_{j\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)\right) \prod_{\mathbf{k}} e^{\frac{1}{2} \left( \frac{v_{i\mathbf{k}}^*(t) v_{j\mathbf{k}}(t) - v_{i\mathbf{k}}(t) v_{j\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}^2} \right)}. \quad (193)$$

From the definition  $B_{01}(t) = \langle B_0^+(t) B_1^-(t) \rangle$  using the displacement operator we have:

$$\langle B_0^+(t) B_1^-(t) \rangle = B_{01}(t) \quad (194)$$

$$= \left\langle \prod_{\mathbf{k}} D\left(\frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}}\right) \prod_{\mathbf{k}} D\left(-\frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}}\right) \right\rangle \quad (195)$$

$$= \left\langle \prod_{\mathbf{k}} \left( D\left(\frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}}\right) D\left(-\frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}}\right) \right) \right\rangle \quad (196)$$

$$= \left\langle \prod_{\mathbf{k}} \left( D\left(\frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} - \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}}\right) e^{\frac{1}{2} \left( \frac{v_{0\mathbf{k}}^*(t) v_{1\mathbf{k}}(t) - v_{0\mathbf{k}}(t) v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}^2} \right)} \right) \right\rangle \quad (197)$$

$$= \prod_{\mathbf{k}} \left( \left\langle D\left(\frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} - \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}}\right) \right\rangle e^{\frac{1}{2} \left( \frac{v_{0\mathbf{k}}^*(t) v_{1\mathbf{k}}(t) - v_{0\mathbf{k}}(t) v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}^2} \right)} \right) \quad (198)$$

$$= \prod_{\mathbf{k}} \left( \exp\left(-\frac{1}{2} \left| \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} - \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)\right) e^{\frac{1}{2} \left( \frac{v_{0\mathbf{k}}^*(t) v_{1\mathbf{k}}(t) - v_{0\mathbf{k}}(t) v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}^2} \right)} \right) \quad (199)$$

$$= \exp\left(-\frac{1}{2} \sum_{\mathbf{k}} \left| \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} - \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)\right) \prod_{\mathbf{k}} e^{\frac{1}{2} \left( \frac{v_{0\mathbf{k}}^*(t) v_{1\mathbf{k}}(t) - v_{0\mathbf{k}}(t) v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}^2} \right)}. \quad (200)$$

We can check:

$$\langle B_0^+(t) B_1^-(t) \rangle = B_{01}(t) \quad (201)$$

$$= \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \left| \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} - \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \prod_{\mathbf{k}} e^{\frac{1}{2} \left( \frac{v_{0\mathbf{k}}^*(t) v_{1\mathbf{k}}(t) - v_{0\mathbf{k}}(t) v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}^2} \right)} \quad (202)$$

$$= \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \left| \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} - \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \prod_{\mathbf{k}} e^{\frac{1}{2} \left( \frac{v_{1\mathbf{k}}^*(t) v_{0\mathbf{k}}(t) - v_{1\mathbf{k}}(t) v_{0\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}^2} \right)^*} \quad (203)$$

$$= \langle B_1^+(t) B_0^-(t) \rangle^* \quad (204)$$

$$= B_{10}^*(t). \quad (205)$$

The parts of the splitted Hamiltonian are:

$$\overline{H_S}(t) \equiv (\varepsilon_0(t) + R_0(t)) |0\rangle\langle 0| + (\varepsilon_1(t) + R_1(t)) |1\rangle\langle 1| + V_{10}(t) B_{10} \sigma^+ + V_{01}(t) B_{01} \sigma^-, \quad (206)$$

$$\overline{H_I} \equiv V_{10}(t) (B_1^+(t) B_0^-(t) - B_{10}(t)) \sigma^+ + V_{01}(t) (B_0^+(t) B_1^-(t) - B_{01}(t)) \sigma^- + |0\rangle\langle 0| B_{0z}(t) + |1\rangle\langle 1| B_{1z}(t), \quad (207)$$

$$\overline{H_B} \equiv \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} \quad (208)$$

$$= H_B. \quad (209)$$

Note that  $\overline{H_B}$ , which is the bath acting on the effective “system”  $\bar{S}$  in the variational frame, is just the original bath,  $H_B$ , before transforming to the variational frame.

For the Hamiltonian (207) we can verify the condition  $\langle \overline{H_I} \rangle_{\overline{H_B}} = 0$  in the following way:

$$\langle \overline{H_I} \rangle_{\overline{H_B}} = \left\langle \sum_{n\mathbf{k}} \left( (g_{n\mathbf{k}} - v_{n\mathbf{k}}(t)) b_{\mathbf{k}}^\dagger + (g_{n\mathbf{k}} - v_{n\mathbf{k}}(t))^* b_{\mathbf{k}} \right) |n\rangle\langle n| + \sum_{j \neq j'} V_{jj'}(t) |j\rangle\langle j'| \left( B_j^+(t) B_{j'}^-(t) - B_{jj'}(t) \right) \right\rangle_{\overline{H_B}} \quad (210)$$

$$= \left\langle \sum_{n\mathbf{k}} \left( (g_{n\mathbf{k}} - v_{n\mathbf{k}}(t)) b_{\mathbf{k}}^\dagger + (g_{n\mathbf{k}} - v_{n\mathbf{k}}(t))^* b_{\mathbf{k}} \right) |n\rangle\langle n| \right\rangle_{\overline{H_B}} + \left\langle \sum_{j \neq j'} V_{jj'}(t) |j\rangle\langle j'| \left( B_j^+(t) B_{j'}^-(t) - B_{jj'}(t) \right) \right\rangle_{\overline{H_B}} \quad (211)$$

$$= \sum_{n\mathbf{k}} \left( \left\langle (g_{n\mathbf{k}} - v_{n\mathbf{k}}(t)) b_{\mathbf{k}}^\dagger \right\rangle_{\overline{H_B}} + \left\langle (g_{n\mathbf{k}} - v_{n\mathbf{k}}(t))^* b_{\mathbf{k}} \right\rangle_{\overline{H_B}} \right) |n\rangle\langle n| + \sum_{j \neq j'} |j\rangle\langle j'| \left( \left\langle V_{jj'}(t) B_j^+(t) B_{j'}^-(t) \right\rangle_{\overline{H_B}} - \left\langle V_{jj'}(t) B_{jj'}(t) \right\rangle_{\overline{H_B}} \right) \quad (212)$$

$$= \sum_{n\mathbf{k}} \left( (g_{n\mathbf{k}} - v_{n\mathbf{k}}(t)) \left\langle b_{\mathbf{k}}^\dagger \right\rangle_{\overline{H_B}} + (g_{n\mathbf{k}} - v_{n\mathbf{k}}(t))^* \left\langle b_{\mathbf{k}} \right\rangle_{\overline{H_B}} \right) |n\rangle\langle n| + \sum_{j \neq j'} |j\rangle\langle j'| V_{jj'}(t) \left( \left\langle B_j^+(t) B_{j'}^-(t) \right\rangle_{\overline{H_B}} - \left\langle B_{jj'}(t) \right\rangle_{\overline{H_B}} \right) \quad (213)$$

$$= \sum_{n\mathbf{k}} \left( (g_{n\mathbf{k}} - v_{n\mathbf{k}}(t)) \left\langle b_{\mathbf{k}}^\dagger \right\rangle_{\overline{H_B}} + (g_{n\mathbf{k}} - v_{n\mathbf{k}}(t))^* \left\langle b_{\mathbf{k}} \right\rangle_{\overline{H_B}} \right) |n\rangle\langle n| + \sum_{j \neq j'} |j\rangle\langle j'| V_{jj'}(t) (B_{jj'}(t) - B_{jj'}(t)) \quad (214)$$

$$= 0. \quad (215)$$

We used (144) and (193) to evaluate the expression. Let's consider the following Hermitian combinations:

$$B_x(t) = B_x^\dagger(t) \quad (216)$$

$$= \frac{B_1^+(t) B_0^-(t) + B_0^+(t) B_1^-(t) - B_{10}(t) - B_{01}(t)}{2}, \quad (217)$$

$$B_y(t) = B_y^\dagger(t) \quad (218)$$

$$= \frac{B_0^+(t) B_1^-(t) - B_1^+(t) B_0^-(t) + B_{10}(t) - B_{01}(t)}{2i}, \quad (219)$$

$$B_{iz}(t) = B_{iz}^\dagger(t) \quad (220)$$

$$= \sum_{\mathbf{k}} \left( (g_{i\mathbf{k}} - v_{i\mathbf{k}}(t)) b_{\mathbf{k}}^\dagger + (g_{i\mathbf{k}} - v_{i\mathbf{k}}(t))^* b_{\mathbf{k}} \right). \quad (221)$$

Writing the equations (206) and (207) using the previous combinations we obtain that:

$$\overline{H_S}(t) = \sum_{j \in \{0,1\}} (\varepsilon_j(t) + R_j(t)) |j\rangle\langle j| + V_{10}(t) B_{10}(t) \sigma^+ + V_{01}(t) B_{01}(t) \sigma^- \quad (222)$$

$$= \sum_{j \in \{0,1\}} (\varepsilon_j(t) + R_j(t)) |j\rangle\langle j| + V_{10}(t) B_{10}(t) \frac{\sigma_x + i\sigma_y}{2} + V_{01}(t) B_{01}(t) \frac{\sigma_x - i\sigma_y}{2} \quad (223)$$

$$= \sum_{j \in \{0,1\}} (\varepsilon_j(t) + R_j(t)) |j\rangle\langle j| + V_{10}(t) (B_{10}^{\Re}(t) + iB_{10}^{\Im}(t)) \frac{\sigma_x + i\sigma_y}{2} + V_{01}(t) (B_{10}^{\Re}(t) - iB_{10}^{\Im}(t)) \frac{\sigma_x - i\sigma_y}{2} \quad (224)$$

$$= \sum_{j \in \{0,1\}} (\varepsilon_j(t) + R_j(t)) |j\rangle\langle j| + B_{10}^{\Re}(t) \left( V_{10}(t) \frac{\sigma_x + i\sigma_y}{2} + V_{01}(t) \frac{\sigma_x - i\sigma_y}{2} \right) + iB_{10}^{\Im}(t) \left( V_{10}(t) \frac{\sigma_x + i\sigma_y}{2} - V_{01}(t) \frac{\sigma_x - i\sigma_y}{2} \right) \quad (225)$$

$$= \sum_{j \in \{0,1\}} (\varepsilon_j(t) + R_j(t)) |j\rangle\langle j| + B_{10}^{\Re}(t) \left( \sigma_x \frac{V_{10}(t) + V_{01}(t)}{2} + i\sigma_y \frac{V_{10}(t) - V_{01}(t)}{2} \right) + iB_{10}^{\Im}(t) \left( \sigma_x \frac{V_{10}(t) - V_{01}(t)}{2} + i\sigma_y \frac{V_{10}(t) + V_{01}(t)}{2} \right) \quad (226)$$

$$= \sum_{j \in \{0,1\}} (\varepsilon_j(t) + R_j(t)) |j\rangle\langle j| + B_{10}^{\Re}(t) (\sigma_x V_{10}^{\Re}(t) - \sigma_y V_{10}^{\Im}(t)) + iB_{10}^{\Im}(t) (i\sigma_x V_{10}^{\Im}(t) + i\sigma_y V_{10}^{\Re}(t)) \quad (227)$$

$$= (\varepsilon_0(t) + R_0(t)) |0\rangle\langle 0| + (\varepsilon_1(t) + R_1(t)) |1\rangle\langle 1| + B_{10}^{\Re}(t) (\sigma_x V_{10}^{\Re}(t) - \sigma_y V_{10}^{\Im}(t)) + iB_{10}^{\Im}(t) (i\sigma_x V_{10}^{\Im}(t) + i\sigma_y V_{10}^{\Re}(t)) \quad (228)$$

$$= (\varepsilon_0(t) + R_0(t)) |0\rangle\langle 0| + (\varepsilon_1(t) + R_1(t)) |1\rangle\langle 1| + (\sigma_x B_{10}^{\Re}(t) V_{10}^{\Re}(t) - \sigma_y B_{10}^{\Re}(t) V_{10}^{\Im}(t) - (\sigma_x B_{10}^{\Im}(t) V_{10}^{\Im}(t) + \sigma_y B_{10}^{\Im}(t) V_{10}^{\Re}(t))) \quad (229)$$

$$= (\varepsilon_0(t) + R_0(t)) |0\rangle\langle 0| + (\varepsilon_1(t) + R_1(t)) |1\rangle\langle 1| + \sigma_x (B_{10}^{\Re}(t) V_{10}^{\Re}(t) - B_{10}^{\Im}(t) V_{10}^{\Im}(t)) - \sigma_y (B_{10}^{\Re}(t) V_{10}^{\Im}(t) + B_{10}^{\Im}(t) V_{10}^{\Re}(t)) \quad (230)$$

$$= (\varepsilon_0(t) + R_0(t)) |0\rangle\langle 0| + (\varepsilon_1(t) + R_1(t)) |1\rangle\langle 1| + \sigma_x (B_{10}^{\Re}(t) V_{10}^{\Re}(t) - B_{10}^{\Im}(t) V_{10}^{\Im}(t)) - \sigma_y (B_{10}^{\Re}(t) V_{10}^{\Im}(t) + B_{10}^{\Im}(t) V_{10}^{\Re}(t)) \quad (231)$$

$$\overline{H_I} = V_{10}(t) (\sigma^+ B_1^+(t) B_0^-(t) - \sigma^+ B_{10}(t)) + V_{01}(t) (\sigma^- B_0^+(t) B_1^-(t) - \sigma^- B_{01}(t)) + |0\rangle\langle 0| B_{0z}(t) + |1\rangle\langle 1| B_{1z}(t) \quad (232)$$

$$= |0\rangle\langle 0| B_{0z}(t) + |1\rangle\langle 1| B_{1z}(t) + (V_{10}^{\Re}(t) + iV_{10}^{\Im}(t)) (\sigma^+ B_1^+(t) B_0^-(t) - \sigma^+ B_{10}(t)) + (V_{10}^{\Re}(t) - iV_{10}^{\Im}(t)) (\sigma^- B_0^+(t) B_1^-(t) - \sigma^- B_{01}(t)) \quad (233)$$

$$= \sum_i B_{iz}(t) |i\rangle\langle i| + V_{10}^{\Re}(t) (\sigma^+ B_1^+(t) B_0^-(t) - \sigma^+ B_{10}(t) + \sigma^- B_0^+(t) B_1^-(t) - \sigma^- B_{01}(t)) + iV_{10}^{\Im}(t) (\sigma^+ B_1^+(t) B_0^-(t) - \sigma^+ B_{10}(t) - \sigma^- B_{01}(t) + \sigma^- B_0^+(t) B_1^-(t)) \quad (234)$$

$$= \sum_i B_{iz}(t) |i\rangle\langle i| + V_{10}^{\Re}(t) \left( \frac{\sigma_x + i\sigma_y}{2} B_1^+(t) B_0^-(t) - \frac{\sigma_x + i\sigma_y}{2} B_{10}(t) + \frac{\sigma_x - i\sigma_y}{2} B_0^+(t) B_1^-(t) - \frac{\sigma_x - i\sigma_y}{2} B_{01}(t) \right) \quad (235)$$

$$= \sum_i B_{iz}(t) |i\rangle\langle i| + V_{10}^{\Re}(t) \left( \frac{\sigma_x + i\sigma_y}{2} B_1^+(t) B_0^-(t) - \frac{\sigma_x + i\sigma_y}{2} B_{10}(t) + \frac{\sigma_x - i\sigma_y}{2} B_0^+(t) B_1^-(t) - \frac{\sigma_x - i\sigma_y}{2} B_{01}(t) \right) \quad (236)$$

$$+ iV_{10}^{\Im}(t) \left( \frac{\sigma_x + i\sigma_y}{2} B_1^+(t) B_0^-(t) - \frac{\sigma_x + i\sigma_y}{2} B_{10}(t) - \frac{\sigma_x - i\sigma_y}{2} B_0^+(t) B_1^-(t) + \frac{\sigma_x - i\sigma_y}{2} B_{01}(t) \right) \quad (237)$$

$$= \sum_i B_{iz}(t) |i\rangle\langle i| + V_{10}^{\Re}(t) \left( \sigma_x \frac{B_1^+(t) B_0^-(t) + B_0^+(t) B_1^-(t) - B_{10}(t) - B_{01}(t)}{2} + i\sigma_y \frac{B_1^+(t) B_0^-(t) - B_0^+(t) B_1^-(t) - B_{10}(t) + B_{01}(t)}{2} \right) \quad (238)$$

$$+ iV_{10}^{\Im}(t) \left( \sigma_x \frac{B_1^+(t) B_0^-(t) - B_0^+(t) B_1^-(t) - B_{10}(t) + B_{01}(t)}{2} + i\sigma_y \frac{B_1^+(t) B_0^-(t) + B_0^+(t) B_1^-(t) - B_{10}(t) - B_{01}(t)}{2} \right) \quad (239)$$

$$= \sum_i B_{iz}(t) |i\rangle\langle i| + V_{10}^{\Re}(t) (\sigma_x B_x(t) + \sigma_y B_y(t)) + V_{10}^{\Im}(t) \left( i\sigma_x \frac{B_1^+(t) B_0^-(t) - B_0^+(t) B_1^-(t) - B_{10}(t) + B_{01}(t)}{2} - \sigma_y \frac{B_1^+(t) B_0^-(t) + B_0^+(t) B_1^-(t) - B_{10}(t) - B_{01}(t)}{2} \right) \quad (240)$$

$$= \sum_i B_{iz}(t) |i\rangle\langle i| + V_{10}^{\Re}(t) (\sigma_x B_x(t) + \sigma_y B_y(t)) + V_{10}^{\Im}(t) \left( i^2 \sigma_x \frac{B_1^+(t) B_0^-(t) - B_0^+(t) B_1^-(t) - B_{10}(t) + B_{01}(t)}{2i} - \sigma_y \frac{B_1^+(t) B_0^-(t) + B_0^+(t) B_1^-(t) - B_{10}(t) - B_{01}(t)}{2} \right) \quad (241)$$

$$= \sum_i B_{iz}(t) |i\rangle\langle i| + V_{10}^{\Re}(t) (\sigma_x B_x(t) + \sigma_y B_y(t)) + V_{10}^{\Im}(t) \left( i^2 \sigma_x \frac{B_1^+ B_0^- - B_0^+ B_1^- - B_{10} + B_{01}}{2i} - \sigma_y \frac{B_1^+ B_0^- + B_0^+ B_1^- - B_{10} - B_{01}}{2} \right) \quad (242)$$

### III. FREE-ENERGY MINIMIZATION

The true free energy  $A$  is bounded by the Bogoliubov inequality:

$$A \leq A_B \equiv -\frac{1}{\beta} \ln \left( \text{Tr} \left( e^{-\beta(\overline{H_S}(t) + \overline{H_B})} \right) \right) + \langle \overline{H_I} \rangle_{\overline{H_S}(t) + \overline{H_B}} + O \left( \langle \overline{H_I}^2 \rangle_{\overline{H_S}(t) + \overline{H_B}} \right). \quad (245)$$

We will optimize the set of variational parameters  $\{v_{i\mathbf{k}}(t)\}$  in order to minimize  $A_B$  (i.e. to make it as close to the true free energy  $A$  as possible). Neglecting the higher order terms and using  $\langle \overline{H_I} \rangle_{\overline{H_S}(t) + \overline{H_B}} = 0$  we can obtain the following condition to obtain the set  $\{v_{i\mathbf{k}}(t)\}$ :

$$\frac{\partial A_B}{\partial v_{i\mathbf{k}}(t)} = 0. \quad (246)$$

Using this condition and given that  $[\overline{H_S}(t), \overline{H_B}] = 0$ , we have:

$$e^{-\beta(\overline{H_S}(t) + \overline{H_B})} = e^{-\beta\overline{H_S}(t)} e^{-\beta\overline{H_B}}. \quad (247)$$

Then using the fact that  $\overline{H_S}(t)$  and  $\overline{H_B}$  relate to different Hilbert spaces, we obtain:

$$\text{Tr} \left( e^{-\beta\overline{H_S}(t)} e^{-\beta\overline{H_B}} \right) = \text{Tr} \left( e^{-\beta\overline{H_S}(t)} \right) \text{Tr} \left( e^{-\beta\overline{H_B}} \right). \quad (248)$$

So Eq. (246) becomes:

$$\frac{\partial A_B}{\partial v_{i\mathbf{k}}(t)} = -\frac{1}{\beta} \frac{\partial \ln \left( \text{Tr} \left( e^{-\beta(\overline{H_S}(t) + \overline{H_B})} \right) \right)}{\partial v_{i\mathbf{k}}(t)} \quad (249)$$

$$= -\frac{1}{\beta} \frac{\partial \ln \left( \text{Tr} \left( e^{-\beta\overline{H_S}(t)} \right) \text{Tr} \left( e^{-\beta\overline{H_B}} \right) \right)}{\partial v_{i\mathbf{k}}(t)} \quad (250)$$

$$= -\frac{1}{\beta} \frac{\partial \left( \ln \left( \text{Tr} \left( e^{-\beta\overline{H_S}(t)} \right) \right) + \ln \left( \text{Tr} \left( e^{-\beta\overline{H_B}} \right) \right) \right)}{\partial v_{i\mathbf{k}}(t)} \quad (251)$$

$$= -\frac{1}{\beta} \frac{\partial \ln \left( \text{Tr} \left( e^{-\beta\overline{H_S}(t)} \right) \right)}{\partial v_{i\mathbf{k}}(t)} - \frac{1}{\beta} \frac{\partial \ln \left( \text{Tr} \left( e^{-\beta\overline{H_B}} \right) \right)}{\partial v_{i\mathbf{k}}(t)} \quad (252)$$

$$= 0 \quad (\text{by Eq. (246)}). \quad (253)$$

But since  $\overline{H_B} = H_B$  which doesn't contain any  $v_{i\mathbf{k}}(t)$ , a derivative of any function of  $H_B$  that does not introduce new  $v_{i\mathbf{k}}(t)$  will be zero. We therefore require the following:

$$\frac{\partial \ln \left( \text{Tr} \left( e^{-\beta\overline{H_S}(t)} \right) \right)}{\partial v_{i\mathbf{k}}(t)} = \frac{1}{e^{-\beta\overline{H_S}(t)}} \frac{\partial \text{Tr} \left( e^{-\beta\overline{H_S}(t)} \right)}{\partial v_{i\mathbf{k}}(t)} \quad (254)$$

$$= 0. \quad (255)$$

This means we need to impose:

$$\frac{\partial \text{Tr} \left( e^{-\beta\overline{H_S}(t)} \right)}{\partial v_{i\mathbf{k}}(t)} = 0. \quad (256)$$

First we look at:



$$-\beta \overline{H_S}(t) = -\beta \left( (\varepsilon_0(t) + R_0(t)) |0\rangle\langle 0| + (\varepsilon_1(t) + R_1(t)) |1\rangle\langle 1| + V_{10}(t) B_{10}(t) \sigma^+ + V_{01}(t) B_{01}(t) \sigma^- \right). \quad (257)$$

Then the eigenvalues of  $-\beta \overline{H_S}(t)$  satisfy the following relationship deduced from the Caley-Hamilton theorem:

$$\lambda^2 - \text{Tr}(-\beta \overline{H_S}(t)) + \text{Det}(-\beta \overline{H_S}(t)) = 0. \quad (258)$$

Let's define:

$$\varepsilon(t) \equiv \text{Tr}(\overline{H_S}(t)), \quad (259)$$

$$\eta \equiv \sqrt{(\text{Tr}(\overline{H_S}(t)))^2 - 4\text{Det}(\overline{H_S}(t))}. \quad (260)$$

The solutions of the equation (258) are:

$$\lambda = \beta \frac{-\text{Tr}(\overline{H_S}(t)) \pm \sqrt{(\text{Tr}(\overline{H_S}(t)))^2 - 4\text{Det}(\overline{H_S}(t))}}{2} \quad (261)$$

$$= \beta \frac{-\varepsilon(t) \pm \eta(t)}{2} \quad (262)$$

$$= -\beta \frac{\varepsilon(t) \mp \eta(t)}{2}. \quad (263)$$

The value of  $\text{Tr}(e^{-\beta \overline{H_S}(t)})$  can be written in terms of this eigenvalues as (since there's only 2 eigenvalues of a  $2 \times 2$  matrix):

$$\text{Tr}(e^{-\beta \overline{H_S}(t)}) = \exp\left(-\frac{\varepsilon(t)\beta}{2}\right) \exp\left(\frac{\eta(t)\beta}{2}\right) + \exp\left(-\frac{\varepsilon(t)\beta}{2}\right) \exp\left(-\frac{\eta(t)\beta}{2}\right) \quad (264)$$

$$= 2\exp\left(-\frac{\varepsilon(t)\beta}{2}\right) \cosh\left(\frac{\eta(t)\beta}{2}\right). \quad (265)$$

Given that  $v_{ik}(t)$  is a complex number then we will optimize in the real and complex parts of this element, this can be seen in the following reasoning.

Using the chain rule on the function  $\text{Tr}(e^{-\beta \overline{H_S}(t)}) = A(\varepsilon(t), \eta(t))$  to calculate  $\frac{\partial \text{Tr}(e^{-\beta \overline{H_S}(t)})}{\partial v_{ik}^{\Re}(t)}$  can lead to:

$$\frac{\partial \text{Tr}(e^{-\beta \overline{H_S}(t)})}{\partial v_{ik}^{\Re}(t)} = \frac{\partial \left( 2\exp\left(-\frac{\varepsilon(t)\beta}{2}\right) \cosh\left(\frac{\eta(t)\beta}{2}\right) \right)}{\partial v_{ik}^{\Re}(t)} \quad (266)$$

$$= 2 \left( -\frac{\beta}{2} \frac{\partial \varepsilon(t)}{\partial v_{ik}^{\Re}(t)} \right) \exp\left(-\frac{\varepsilon(t)\beta}{2}\right) \cosh\left(\frac{\eta(t)\beta}{2}\right) + 2 \left( \frac{\beta}{2} \frac{\partial \eta(t)}{\partial v_{ik}^{\Re}(t)} \right) \exp\left(-\frac{\varepsilon(t)\beta}{2}\right) \sinh\left(\frac{\eta(t)\beta}{2}\right) \quad (267)$$

$$= -\beta \exp\left(-\frac{\varepsilon(t)\beta}{2}\right) \left( \frac{\partial \varepsilon(t)}{\partial v_{ik}^{\Re}(t)} \cosh\left(\frac{\eta(t)\beta}{2}\right) - \frac{\partial \eta(t)}{\partial v_{ik}^{\Re}(t)} \sinh\left(\frac{\eta(t)\beta}{2}\right) \right). \quad (268)$$

Making the derivate equal to zero make us suitable to write:

$$\frac{\partial \varepsilon(t)}{\partial v_{ik}^{\Re}(t)} \cosh\left(\frac{\eta(t)\beta}{2}\right) - \frac{\partial \eta(t)}{\partial v_{ik}^{\Re}(t)} \sinh\left(\frac{\eta(t)\beta}{2}\right) = 0. \quad (269)$$

The derivates included in the expression given are related to:

$$\langle B_0^+(t) B_1^-(t) \rangle = \left( \prod_{\mathbf{k}} e^{\frac{1}{2} \left( \frac{v_{0\mathbf{k}}^*(t) v_{1\mathbf{k}}(t) - v_{0\mathbf{k}}(t) v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}^2} \right)} \right) \left( \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \left| \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} - \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \right) \quad (270)$$

$$= \left( \prod_{\mathbf{k}} e^{\frac{1}{2} \left( \frac{v_{1\mathbf{k}}^*(t) v_{0\mathbf{k}}(t) - v_{1\mathbf{k}}(t) v_{0\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}^2} \right)} \right)^* \left( \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \left| \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} - \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \right) \quad (271)$$

$$= \langle B_1^+(t) B_0^-(t) \rangle^*, \quad (272)$$

$$R_i(t) = \sum_{\mathbf{k}} \left( \frac{|v_{i\mathbf{k}}(t)|^2}{\omega_{\mathbf{k}}} - \left( g_{i\mathbf{k}} \frac{v_{i\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} + g_{i\mathbf{k}}^* \frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right) \right) \quad (273)$$

$$= \sum_{\mathbf{k}} \left( \frac{|v_{i\mathbf{k}}(t)|^2}{\omega_{\mathbf{k}}} - g_{i\mathbf{k}} \frac{v_{i\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}} - g_{i\mathbf{k}}^* \frac{v_{i\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right), \quad (274)$$

$$\langle B_0^+(t) B_1^-(t) \rangle = \left( \prod_{\mathbf{k}} e^{\frac{1}{2} \left( \frac{v_{0\mathbf{k}}^*(t) v_{1\mathbf{k}}(t) - v_{0\mathbf{k}}(t) v_{1\mathbf{k}}^*(t)}{\omega_{\mathbf{k}}^2} \right)} \right) \left( \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \left| \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} - \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \right) \quad (275)$$

$$= \left( \prod_{\mathbf{k}} \exp \left( \frac{v_{0\mathbf{k}}^*(t) v_{1\mathbf{k}}(t) - v_{0\mathbf{k}}(t) v_{1\mathbf{k}}^*(t)}{2\omega_{\mathbf{k}}^2} \right) \right) \left( \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \left| \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} - \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \right), \quad (276)$$

$$v_{0\mathbf{k}}^*(t) v_{1\mathbf{k}}(t) - v_{0\mathbf{k}}(t) v_{1\mathbf{k}}^*(t) = (v_{0\mathbf{k}}^{\Re}(t) - i v_{0\mathbf{k}}^{\Im}(t)) (v_{1\mathbf{k}}^{\Re}(t) + i v_{1\mathbf{k}}^{\Im}(t)) - (v_{0\mathbf{k}}^{\Re}(t) + i v_{0\mathbf{k}}^{\Im}(t)) (v_{1\mathbf{k}}^{\Re}(t) - i v_{1\mathbf{k}}^{\Im}(t)) \quad (277)$$

$$= (v_{0\mathbf{k}}^{\Re}(t) v_{1\mathbf{k}}^{\Re}(t) + i v_{0\mathbf{k}}^{\Re}(t) v_{1\mathbf{k}}^{\Im}(t) - i v_{0\mathbf{k}}^{\Im}(t) v_{1\mathbf{k}}^{\Re}(t) + v_{0\mathbf{k}}^{\Im}(t) v_{1\mathbf{k}}^{\Im}(t)) - (v_{0\mathbf{k}}^{\Re}(t) v_{1\mathbf{k}}^{\Re}(t) - i v_{0\mathbf{k}}^{\Re}(t) v_{1\mathbf{k}}^{\Im}(t) + i v_{0\mathbf{k}}^{\Im}(t) v_{1\mathbf{k}}^{\Re}(t) - v_{0\mathbf{k}}^{\Im}(t) v_{1\mathbf{k}}^{\Im}(t)) \quad (278)$$

$$= 2i (v_{0\mathbf{k}}^{\Re}(t) v_{1\mathbf{k}}^{\Im}(t) - v_{0\mathbf{k}}^{\Im}(t) v_{1\mathbf{k}}^{\Re}(t)), \quad (279)$$

$$|v_{1\mathbf{k}}(t) - v_{0\mathbf{k}}(t)|^2 = (v_{1\mathbf{k}}(t) - v_{0\mathbf{k}}(t)) (v_{1\mathbf{k}}(t) - v_{0\mathbf{k}}(t))^* \quad (280)$$

$$= |v_{1\mathbf{k}}(t)|^2 + |v_{0\mathbf{k}}(t)|^2 - (v_{1\mathbf{k}}(t) v_{0\mathbf{k}}^*(t) + v_{1\mathbf{k}}^*(t) v_{0\mathbf{k}}(t)) \quad (281)$$

$$= (v_{1\mathbf{k}}^{\Re}(t))^2 + (v_{1\mathbf{k}}^{\Im}(t))^2 + (v_{0\mathbf{k}}^{\Re}(t))^2 + (v_{0\mathbf{k}}^{\Im}(t))^2 - ((v_{1\mathbf{k}}^{\Re}(t) + i v_{1\mathbf{k}}^{\Im}(t))(v_{0\mathbf{k}}^{\Re}(t) - i v_{0\mathbf{k}}^{\Im}(t)) + (v_{1\mathbf{k}}^{\Re}(t) - i v_{1\mathbf{k}}^{\Im}(t))(v_{0\mathbf{k}}^{\Re}(t) + i v_{0\mathbf{k}}^{\Im}(t))) \quad (282)$$

$$= (v_{1\mathbf{k}}^{\Re}(t))^2 + (v_{1\mathbf{k}}^{\Im}(t))^2 + (v_{0\mathbf{k}}^{\Re}(t))^2 + (v_{0\mathbf{k}}^{\Im}(t))^2 - 2 (v_{1\mathbf{k}}^{\Re}(t) v_{0\mathbf{k}}^{\Re}(t) + v_{1\mathbf{k}}^{\Im}(t) v_{0\mathbf{k}}^{\Im}(t)) \quad (283)$$

$$= (v_{1\mathbf{k}}^{\Re}(t) - v_{0\mathbf{k}}^{\Re}(t))^2 + (v_{1\mathbf{k}}^{\Im}(t) - v_{0\mathbf{k}}^{\Im}(t))^2. \quad (284)$$

Rewriting in terms of real and imaginary parts.

$$R_i(t) = \sum_{\mathbf{k}} \left( \frac{(v_{i\mathbf{k}}^{\Re}(t))^2 + (v_{i\mathbf{k}}^{\Im}(t))^2}{\omega_{\mathbf{k}}} - \left( g_{i\mathbf{k}} \frac{v_{i\mathbf{k}}^{\Re}(t) - i v_{i\mathbf{k}}^{\Im}(t)}{\omega_{\mathbf{k}}} + g_{i\mathbf{k}}^* \frac{v_{i\mathbf{k}}^{\Re}(t) + i v_{i\mathbf{k}}^{\Im}(t)}{\omega_{\mathbf{k}}} \right) \right) \quad (285)$$

$$= \sum_{\mathbf{k}} \left( \frac{(v_{i\mathbf{k}}^{\Re}(t))^2 + (v_{i\mathbf{k}}^{\Im}(t))^2}{\omega_{\mathbf{k}}} - v_{i\mathbf{k}}^{\Re}(t) \frac{g_{i\mathbf{k}} + g_{i\mathbf{k}}^*}{\omega_{\mathbf{k}}} - i v_{i\mathbf{k}}^{\Im}(t) \frac{g_{i\mathbf{k}}^* - g_{i\mathbf{k}}}{\omega_{\mathbf{k}}} \right), \quad (286)$$

$$\langle B_0^+(t) B_1^-(t) \rangle = \left( \prod_{\mathbf{k}} \exp \left( \frac{v_{0\mathbf{k}}^*(t) v_{1\mathbf{k}}(t) - v_{0\mathbf{k}}(t) v_{1\mathbf{k}}^*(t)}{2\omega_{\mathbf{k}}^2} \right) \right) \left( \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \left| \frac{v_{0\mathbf{k}}(t)}{\omega_{\mathbf{k}}} - \frac{v_{1\mathbf{k}}(t)}{\omega_{\mathbf{k}}} \right|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \right) \quad (287)$$

$$= \left( \prod_{\mathbf{k}} \exp \left( \frac{2i(v_{0\mathbf{k}}^{\Re}(t) v_{1\mathbf{k}}^{\Im}(t) - v_{0\mathbf{k}}^{\Im}(t) v_{1\mathbf{k}}^{\Re}(t))}{2\omega_{\mathbf{k}}^2} \right) \right) \left( \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \frac{(v_{1\mathbf{k}}^{\Re}(t) - v_{0\mathbf{k}}^{\Re}(t))^2 + (v_{1\mathbf{k}}^{\Im}(t) - v_{0\mathbf{k}}^{\Im}(t))^2}{\omega_{\mathbf{k}}^2} \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \right) \quad (288)$$

$$= \left( \prod_{\mathbf{k}} \exp \left( \frac{i(v_{0\mathbf{k}}^{\Re}(t) v_{1\mathbf{k}}^{\Im}(t) - v_{0\mathbf{k}}^{\Im}(t) v_{1\mathbf{k}}^{\Re}(t))}{\omega_{\mathbf{k}}^2} \right) \right) \left( \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \frac{(v_{1\mathbf{k}}^{\Re}(t) - v_{0\mathbf{k}}^{\Re}(t))^2 + (v_{1\mathbf{k}}^{\Im}(t) - v_{0\mathbf{k}}^{\Im}(t))^2}{\omega_{\mathbf{k}}^2} \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \right) \quad (289)$$

Calculating the derivatives respect to  $\alpha_{i\mathbf{k}}^{\Re}$  and  $\alpha_{i\mathbf{k}}^{\Im}$  we have:

$$\frac{\partial \varepsilon(t)}{\partial v_{i\mathbf{k}}^{\Re}} = \frac{\partial (\varepsilon_1(t) + R_1 + \varepsilon_0(t) + R_0)}{\partial v_{i\mathbf{k}}^{\Re}} \quad (290)$$

$$= \frac{\partial \left( \left( \frac{(v_{i\mathbf{k}}^{\Re})^2 + (v_{i\mathbf{k}}^{\Im})^2}{\omega_{\mathbf{k}}} - v_{i\mathbf{k}}^{\Re} \frac{g_{i\mathbf{k}} + g_{i\mathbf{k}}^*}{\omega_{\mathbf{k}}} - i v_{i\mathbf{k}}^{\Im} \frac{g_{i\mathbf{k}}^* - g_{i\mathbf{k}}}{\omega_{\mathbf{k}}} \right) \right)}{\partial v_{i\mathbf{k}}^{\Re}} \quad (291)$$

$$= \frac{2v_{i\mathbf{k}}^{\Re}}{\omega_{\mathbf{k}}} - \frac{g_{i\mathbf{k}} + g_{i\mathbf{k}}^*}{\omega_{\mathbf{k}}}, \quad (292)$$

$$\frac{\partial |B_{10}|^2}{\partial v_{i\mathbf{k}}^{\Re}} = \frac{\partial \left( \exp \left( - \sum_{\mathbf{k}} \frac{(v_{1\mathbf{k}}^{\Re} - v_{0\mathbf{k}}^{\Re})^2 + (v_{1\mathbf{k}}^{\Im} - v_{0\mathbf{k}}^{\Im})^2}{\omega_{\mathbf{k}}^2} \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \right)}{\partial v_{i\mathbf{k}}^{\Re}} \quad (293)$$

$$= - \frac{2(v_{1\mathbf{k}}^{\Re} - v_{0\mathbf{k}}^{\Re})}{\omega_{\mathbf{k}}^2} \frac{\partial (v_{1\mathbf{k}}^{\Re} - v_{0\mathbf{k}}^{\Re})}{\partial v_{i\mathbf{k}}^{\Re}} \exp \left( - \sum_{\mathbf{k}} \frac{(v_{1\mathbf{k}}^{\Re} - v_{0\mathbf{k}}^{\Re})^2 + (v_{1\mathbf{k}}^{\Im} - v_{0\mathbf{k}}^{\Im})^2}{\omega_{\mathbf{k}}^2} \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \quad (294)$$

$$= - \frac{2(v_{1\mathbf{k}}^{\Re} - v_{0\mathbf{k}}^{\Re})}{\omega_{\mathbf{k}}^2} \frac{\partial (v_{1\mathbf{k}}^{\Re} - v_{0\mathbf{k}}^{\Re})}{\partial v_{i\mathbf{k}}^{\Re}} |B_{10}|^2, \quad (295)$$

$$\frac{\partial \eta(t)}{\partial v_{i\mathbf{k}}^{\Re}} = \frac{\partial \sqrt{\left( \text{Tr} \left( \overline{H_{\bar{S}}(t)} \right) \right)^2 - 4 \text{Det} \left( \overline{H_{\bar{S}}(t)} \right)}}{\partial v_{i\mathbf{k}}^{\Re}} \quad (296)$$

$$= \frac{2 \text{Tr} \left( \overline{H_{\bar{S}}(t)} \right) \frac{\partial \text{Tr} \left( \overline{H_{\bar{S}}(t)} \right)}{\partial v_{i\mathbf{k}}^{\Re}} - 4 \frac{\partial \text{Det} \left( \overline{H_{\bar{S}}(t)} \right)}{\partial v_{i\mathbf{k}}^{\Re}}}{2 \sqrt{\left( \text{Tr} \left( \overline{H_{\bar{S}}(t)} \right) \right)^2 - 4 \text{Det} \left( \overline{H_{\bar{S}}(t)} \right)}} \quad (297)$$

$$= \frac{\varepsilon(t) \left( \frac{2v_{i\mathbf{k}}^{\Re}}{\omega_{\mathbf{k}}} - \frac{g_{i\mathbf{k}} + g_{i\mathbf{k}}^*}{\omega_{\mathbf{k}}} \right) - 2 \frac{\partial ((\varepsilon_1(t) + R_1)(\varepsilon_0(t) + R_0) - |V_{10}(t)|^2 |B_{10}(t)|^2)}{\partial v_{i\mathbf{k}}^{\Re}}}{\eta(t)} \quad (298)$$

$$= \frac{\varepsilon(t) \left( \frac{2v_{i\mathbf{k}}^{\Re}}{\omega_{\mathbf{k}}} - \frac{g_{i\mathbf{k}} + g_{i\mathbf{k}}^*}{\omega_{\mathbf{k}}} \right) - 2 \left( (\varepsilon(t) - \varepsilon_i(t) - R_i) \left( \frac{2v_{i\mathbf{k}}^{\Re}}{\omega_{\mathbf{k}}} - \frac{g_{i\mathbf{k}} + g_{i\mathbf{k}}^*}{\omega_{\mathbf{k}}} \right) + \frac{2(v_{1\mathbf{k}}^{\Re} - v_{0\mathbf{k}}^{\Re})}{\omega_{\mathbf{k}}^2} \frac{\partial (v_{1\mathbf{k}}^{\Re} - v_{0\mathbf{k}}^{\Re})}{\partial v_{i\mathbf{k}}^{\Re}} |B_{10}|^2 |V_{10}(t)|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right)}{\eta(t)} \quad (299)$$

$$= \frac{\varepsilon(t) \left( \frac{2v_{i\mathbf{k}}^{\Re}}{\omega_{\mathbf{k}}} - \frac{g_{i\mathbf{k}} + g_{i\mathbf{k}}^*}{\omega_{\mathbf{k}}} \right) - 2 \left( (\varepsilon(t) - \varepsilon_i(t) - R_i) \left( \frac{2v_{i\mathbf{k}}^{\Re}}{\omega_{\mathbf{k}}} - \frac{g_{i\mathbf{k}} + g_{i\mathbf{k}}^*}{\omega_{\mathbf{k}}} \right) + \frac{2(v_{1\mathbf{k}}^{\Re} - v_{0\mathbf{k}}^{\Re})}{\omega_{\mathbf{k}}^2} |B_{10}|^2 |V_{10}(t)|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right)}{\eta(t)} \quad (300)$$

$$= \frac{v_{i\mathbf{k}}^{\Re}}{\omega_{\mathbf{k}}} \left( \frac{2\varepsilon(t) - 4(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{4}{\omega_{\mathbf{k}}} |B_{10}|^2 |V_{10}(t)|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right)}{\eta(t)} \right) + \frac{1}{\eta(t)} \left( - \frac{g_{i\mathbf{k}} + g_{i\mathbf{k}}^*}{\omega_{\mathbf{k}}} \varepsilon(t) \right) \quad (301)$$

$$+ 2(\varepsilon(t) - \varepsilon_i(t) - R_i) \frac{g_{i\mathbf{k}} + g_{i\mathbf{k}}^*}{\omega_{\mathbf{k}}} + 4 \frac{v_{i\mathbf{k}}^{\Re}}{\omega_{\mathbf{k}}^2} |B_{10}|^2 |V_{10}(t)|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right). \quad (302)$$

From the equation (269) and replacing the derivates obtained we have:

$$\tanh \left( \frac{\beta \eta(t)}{2} \right) = \frac{\frac{\partial \varepsilon(t)}{\partial v_{i\mathbf{k}}^{\Re}}}{\frac{\partial \eta(t)}{\partial v_{i\mathbf{k}}^{\Re}}} \quad (303)$$

$$= \frac{\frac{2v_{i\mathbf{k}}^{\Re}}{\omega_{\mathbf{k}}} - \frac{2g_{i\mathbf{k}}^{\Re}}{\omega_{\mathbf{k}}}}{\frac{v_{i\mathbf{k}}^{\Re}}{\omega_{\mathbf{k}}} \left( 2 \frac{\varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{2}{\omega_{\mathbf{k}}} |B_{10}|^2 |V_{10}(t)|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right)}{\eta(t)} \right) + 2 \frac{(\varepsilon(t) - \varepsilon_i(t) - R_i) \frac{g_{i\mathbf{k}}^{\Re}}{\omega_{\mathbf{k}}} + 2 \frac{v_{i\mathbf{k}}^{\Re}}{\omega_{\mathbf{k}}^2} |B_{10}|^2 |V_{10}(t)|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) - \frac{g_{i\mathbf{k}}^{\Re}}{\omega_{\mathbf{k}}} \varepsilon(t)}{\eta(t)}}}. \quad (304)$$

Rearrannng this equation will lead to:

$$\tanh\left(\frac{\beta\eta(t)}{2}\right) = \frac{(2v_{ik}^{\Re} - g_{ik} - g_{ik}^*)\eta(t)}{v_{ik}^{\Re} \left( 2\varepsilon(t) - 4(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{4|V_{10}(t)|^2 |B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right) - (g_{ik} + g_{ik}^*)(\varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i)) + 4\frac{v_{ik}^{\Re}}{\omega_{\mathbf{k}}} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)} \quad (305)$$

$$= \frac{(2v_{ik}^{\Re} - 2g_{ik}^{\Re})\eta(t)}{v_{ik}^{\Re} \left( 2\varepsilon(t) - 4(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{4|V_{10}(t)|^2 |B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right) - 2g_{ik}^{\Re}(\varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i)) + 4\frac{v_{ik}^{\Re}}{\omega_{\mathbf{k}}} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)} \quad (306)$$

$$= \frac{(2v_{ik}^{\Re} - 2g_{ik}^{\Re})\eta(t)}{v_{ik}^{\Re} \left( 2\varepsilon(t) - 4(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{4|V_{10}(t)|^2 |B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right) - 2g_{ik}^{\Re}(2\varepsilon_i(t) + 2R_i - \varepsilon(t)) + 4\frac{v_{ik}^{\Re}}{\omega_{\mathbf{k}}} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)} \quad (307)$$

$$= \frac{(v_{ik}^{\Re} - g_{ik}^{\Re})\eta(t)}{v_{ik}^{\Re} \left( \varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{2|V_{10}(t)|^2 |B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right) - g_{ik}^{\Re}(2\varepsilon_i(t) + 2R_i - \varepsilon(t)) + 2\frac{v_{ik}^{\Re}}{\omega_{\mathbf{k}}} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)} \quad (308)$$

Separating (307) such that the terms with  $v_{ik}$  are located at one side of the equation permit us to write

$$\frac{(v_{ik}^{\Re} - g_{ik}^{\Re})\eta(t)}{\tanh\left(\frac{\beta\eta(t)}{2}\right)} = v_{ik}^{\Re} \left( \varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{2|V_{10}(t)|^2 |B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right) - g_{ik}^{\Re}(2\varepsilon_i(t) + 2R_i - \varepsilon(t)) + 2\frac{v_{ik}^{\Re}}{\omega_{\mathbf{k}}} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right), \quad (309)$$

$$v_{ik}^{\Re} - g_{ik}^{\Re} = v_{ik}^{\Re} \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} \left( \varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{2|V_{10}(t)|^2 |B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right) - \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} g_{ik}^{\Re}(2\varepsilon_i(t) + 2R_i - \varepsilon(t)) + 2\frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} \frac{v_{ik}^{\Re}}{\omega_{\mathbf{k}}} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right), \quad (310)$$

$$v_{ik}^{\Re} = \frac{g_{ik}^{\Re} \left( 1 - \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} (2\varepsilon_i(t) + 2R_i - \varepsilon(t)) + 2\frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)\omega_{\mathbf{k}}} \frac{v_{ik}^{\Re}}{g_{ik}^{\Re}} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right) \right)}{1 - \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} \left( \varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{2|V_{10}(t)|^2 |B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right)}, \quad (311)$$

$$v_{ik}^{\Re} = \frac{g_{ik}^{\Re} \left( 1 - \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} (2\varepsilon_i(t) + 2R_i - \varepsilon(t)) + 2\frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)\omega_{\mathbf{k}}} \frac{v_{ik}^{\Re}}{g_{ik}^{\Re}} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right) \right)}{1 - \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} \left( \varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{2|V_{10}(t)|^2 |B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right)}. \quad (312)$$

The imaginary part can be found in the following way:

$$\frac{\partial \varepsilon(t)}{\partial v_{ik}^{\Im}} = \frac{\partial (\varepsilon_1(t) + R_1 + \varepsilon_0(t) + R_0)}{\partial v_{ik}^{\Im}} \quad (313)$$

$$= \frac{\partial \left( \left( \frac{(v_{ik}^{\Re})^2 + (v_{ik}^{\Im})^2}{\omega_{\mathbf{k}}} - v_{ik}^{\Re} \frac{g_{ik} + g_{ik}^*}{\omega_{\mathbf{k}}} - i v_{ik}^{\Im} \frac{g_{ik}^* - g_{ik}}{\omega_{\mathbf{k}}} \right) \right)}{\partial v_{ik}^{\Im}} \quad (314)$$

$$= 2 \frac{v_{ik}^{\Im}}{\omega_{\mathbf{k}}} - i \frac{g_{ik}^* - g_{ik}}{\omega_{\mathbf{k}}}, \quad (315)$$

$$\frac{\partial |B_{10}|^2}{\partial v_{ik}^{\Im}} = \frac{\partial \left( \exp \left( - \sum_{\mathbf{k}} \frac{(v_{1\mathbf{k}}^{\Re} - v_{0\mathbf{k}}^{\Re})^2 + (v_{1\mathbf{k}}^{\Im} - v_{0\mathbf{k}}^{\Im})^2}{\omega_{\mathbf{k}}^2} \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right) \right) \right)}{\partial v_{ik}^{\Im}} \quad (316)$$

$$= -\frac{2(v_{1\mathbf{k}}^{\Im} - v_{0\mathbf{k}}^{\Im})}{\omega_{\mathbf{k}}^2} \frac{\partial(v_{1\mathbf{k}}^{\Im} - v_{0\mathbf{k}}^{\Im})}{\partial v_{i\mathbf{k}}^{\Im}} \exp\left(-\sum_{\mathbf{k}} \frac{(v_{1\mathbf{k}}^{\Re} - v_{0\mathbf{k}}^{\Re})^2 + (v_{1\mathbf{k}}^{\Im} - v_{0\mathbf{k}}^{\Im})^2}{\omega_{\mathbf{k}}^2} \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)\right) \quad (317)$$

$$= -\frac{2(v_{1\mathbf{k}}^{\Im} - v_{0\mathbf{k}}^{\Im})}{\omega_{\mathbf{k}}^2} \frac{\partial(v_{1\mathbf{k}}^{\Im} - v_{0\mathbf{k}}^{\Im})}{\partial v_{i\mathbf{k}}^{\Im}} |B_{10}|^2, \quad (318)$$

$$\frac{\partial\eta(t)}{\partial v_{i\mathbf{k}}^{\Re}} = \frac{\partial\sqrt{\left(\text{Tr}\left(\overline{H_{\bar{S}}(t)}\right)\right)^2 - 4\text{Det}\left(\overline{H_{\bar{S}}(t)}\right)}}{\partial v_{i\mathbf{k}}^{\Re}} \quad (319)$$

$$= \frac{2\text{Tr}\left(\overline{H_{\bar{S}}(t)}\right) \frac{\partial\text{Tr}\left(\overline{H_{\bar{S}}(t)}\right)}{\partial v_{i\mathbf{k}}^{\Re}} - 4\frac{\partial\text{Det}\left(\overline{H_{\bar{S}}(t)}\right)}{\partial v_{i\mathbf{k}}^{\Re}}}{2\sqrt{\left(\text{Tr}\left(\overline{H_{\bar{S}}(t)}\right)\right)^2 - 4\text{Det}\left(\overline{H_{\bar{S}}(t)}\right)}} \quad (320)$$

$$= \frac{\varepsilon(t) \left(2\frac{v_{i\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}} - i\frac{g_{i\mathbf{k}}^* - g_{i\mathbf{k}}}{\omega_{\mathbf{k}}}\right) - 2\frac{\partial((\varepsilon_1(t) + R_1)(\varepsilon_0(t) + R_0) - |V_{10}(t)|^2 |B_{10}(t)|^2)}{\partial v_{i\mathbf{k}}^{\Re}}}{\eta(t)} \quad (321)$$

$$= \frac{\varepsilon(t) \left(2\frac{v_{i\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}} - i\frac{g_{i\mathbf{k}}^* - g_{i\mathbf{k}}}{\omega_{\mathbf{k}}}\right) - 2\left(\varepsilon(t) - \varepsilon_i(t) - R_i\right) \left(2\frac{v_{i\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}} - i\frac{g_{i\mathbf{k}}^* - g_{i\mathbf{k}}}{\omega_{\mathbf{k}}}\right) + \frac{2(v_{1\mathbf{k}}^{\Im} - v_{0\mathbf{k}}^{\Im})}{\omega_{\mathbf{k}}^2} \frac{\partial(v_{1\mathbf{k}}^{\Im} - v_{0\mathbf{k}}^{\Im})}{\partial v_{i\mathbf{k}}^{\Re}} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\eta(t)} \quad (322)$$

$$= \frac{\varepsilon(t) \left(2\frac{v_{i\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}} - i\frac{g_{i\mathbf{k}}^* - g_{i\mathbf{k}}}{\omega_{\mathbf{k}}}\right) - 2\left(\varepsilon(t) - \varepsilon_i(t) - R_i\right) \left(2\frac{v_{i\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}} - i\frac{g_{i\mathbf{k}}^* - g_{i\mathbf{k}}}{\omega_{\mathbf{k}}}\right) + \frac{2(v_{i\mathbf{k}}^{\Im} - v_{i'\mathbf{k}}^{\Im})}{\omega_{\mathbf{k}}^2} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\eta(t)} \quad (323)$$

$$= \frac{v_{i\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}} \left( \frac{2\varepsilon(t) - 4(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{4}{\omega_{\mathbf{k}}} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\eta(t)} \right) + \frac{1}{\eta(t)} \left( -i\frac{g_{i\mathbf{k}}^* - g_{i\mathbf{k}}}{\omega_{\mathbf{k}}} \varepsilon(t) + 2(\varepsilon(t) - \varepsilon_i(t) - R_i) i\frac{g_{i\mathbf{k}}^* - g_{i\mathbf{k}}}{\omega_{\mathbf{k}}} + 4\frac{v_{i'\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}^2} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right) \right). \quad (324)$$

From the equation (269) and replacing the derivates obtained we have:

$$\tanh\left(\frac{\beta\eta(t)}{2}\right) = \frac{\frac{\partial\varepsilon(t)}{\partial v_{i\mathbf{k}}^{\Re}}}{\frac{\partial\eta(t)}{\partial v_{i\mathbf{k}}^{\Re}}} \quad (325)$$

$$= \frac{2\frac{v_{i\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}} - i\frac{g_{i\mathbf{k}}^* - g_{i\mathbf{k}}}{\omega_{\mathbf{k}}}}{\frac{v_{i\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}} \left( \frac{2\varepsilon(t) - 4(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{4}{\omega_{\mathbf{k}}} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\eta(t)} \right) + \frac{1}{\eta(t)} \left( \frac{(g_{i\mathbf{k}}^*)^{\Im}}{\omega_{\mathbf{k}}} \varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i) \frac{(g_{i\mathbf{k}}^*)^{\Im}}{\omega_{\mathbf{k}}} + 2\frac{v_{i'\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}^2} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right) \right)}. \quad (326)$$

Rearranging this equation will lead to:

$$\tanh\left(\frac{\beta\eta(t)}{2}\right) = \frac{\left(2\frac{v_{i\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}} - i\frac{g_{i\mathbf{k}}^* - g_{i\mathbf{k}}}{\omega_{\mathbf{k}}}\right) \eta(t)}{v_{i\mathbf{k}}^{\Im} \left( 2\varepsilon(t) - 4(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{4|V_{10}(t)|^2 |B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right) - i\left(g_{i\mathbf{k}}^* - g_{i\mathbf{k}}\right) (\varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i)) + 4\frac{v_{i'\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}^2} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)} \quad (327)$$

$$= \frac{2\left(\frac{v_{i\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}} - g_{i\mathbf{k}}^{\Im}\right) \eta(t)}{v_{i\mathbf{k}}^{\Im} \left( 2\varepsilon(t) - 4(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{4|V_{10}(t)|^2 |B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right) - 2g_{i\mathbf{k}}^{\Im} (\varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i)) + 4\frac{v_{i'\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}^2} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)} \quad (328)$$

$$= \frac{2\left(\frac{v_{i\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}} - g_{i\mathbf{k}}^{\Im}\right) \eta(t)}{v_{i\mathbf{k}}^{\Im} \left( 2\varepsilon(t) - 4(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{4|V_{10}(t)|^2 |B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right) - 2g_{i\mathbf{k}}^{\Im} (2\varepsilon_i(t) + 2R_i - \varepsilon(t)) + 4\frac{v_{i'\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}^2} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)} \quad (329)$$

$$= \frac{\left(\frac{v_{i\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}} - g_{i\mathbf{k}}^{\Im}\right) \eta(t)}{v_{i\mathbf{k}}^{\Im} \left( \varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{2|V_{10}(t)|^2 |B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right) - g_{i\mathbf{k}}^{\Im} (2\varepsilon_i(t) + 2R_i - \varepsilon(t)) + 2\frac{v_{i'\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}^2} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}. \quad (330)$$

Separating (330) such that the terms with  $v_{i\mathbf{k}}$  are located at one side of the equation permit us to write

$$\frac{(v_{i\mathbf{k}}^{\Im} - g_{i\mathbf{k}}^{\Im})\eta(t)}{\tanh\left(\frac{\beta\eta(t)}{2}\right)} = v_{i\mathbf{k}}^{\Im} \left( \varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{2|V_{10}(t)B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right) - g_{i\mathbf{k}}^{\Im} (2\varepsilon_i(t) + 2R_i - \varepsilon(t)) + 2 \frac{v_{i'\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}} |B_{10}V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right), \quad (331)$$

$$v_{i\mathbf{k}}^{\Im} - g_{i\mathbf{k}}^{\Im} = v_{i\mathbf{k}}^{\Im} \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} \left( \varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{2|V_{10}(t)B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right) - \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} g_{i\mathbf{k}}^{\Im} (2\varepsilon_i(t) + 2R_i - \varepsilon(t)) \quad (332)$$

$$+ 2 \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} \frac{v_{i'\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}} |B_{10}V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right), \quad (333)$$

$$v_{i\mathbf{k}}^{\Im} = \frac{g_{i\mathbf{k}}^{\Im} \left( 1 - \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} (2\varepsilon_i(t) + 2R_i - \varepsilon(t)) \right) + 2 \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} \frac{v_{i'\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{1 - \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} \left( \varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{2|V_{10}(t)|^2 |B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right)}, \quad (334)$$

$$v_{i\mathbf{k}}^{\Im} = \frac{g_{i\mathbf{k}}^{\Im} \left( 1 - \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} (2\varepsilon_i(t) + 2R_i - \varepsilon(t)) \right) + 2 \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} \frac{v_{i'\mathbf{k}}^{\Im}}{\omega_{\mathbf{k}}} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{1 - \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} \left( \varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{2|V_{10}(t)|^2 |B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right)}. \quad (335)$$

The variational parameters are:

$$v_{i\mathbf{k}}(\omega_{\mathbf{k}}) = v_{i\mathbf{k}}^{\Re}(\omega_{\mathbf{k}}) + i v_{i\mathbf{k}}^{\Im}(\omega_{\mathbf{k}}) \quad (336)$$

$$g_{i\mathbf{k}}^{\Re}(\omega_{\mathbf{k}}) \left( 1 - \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} (2\varepsilon_i(t) + 2R_i - \varepsilon(t)) \right) + 2 \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} \frac{v_{i'\mathbf{k}}^{\Re}(\omega_{\mathbf{k}})}{\omega_{\mathbf{k}}} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right) \\ = \frac{1 - \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} \left( \varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{2|V_{10}(t)|^2 |B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right)}{\quad} \quad (337)$$

$$+ i \frac{g_{i\mathbf{k}}^{\Im}(\omega_{\mathbf{k}}) \left( 1 - \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} (2\varepsilon_i(t) + 2R_i - \varepsilon(t)) \right) + 2 \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} \frac{v_{i'\mathbf{k}}^{\Im}(\omega_{\mathbf{k}})}{\omega_{\mathbf{k}}} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{1 - \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} \left( \varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{2|V_{10}(t)|^2 |B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right)} \quad (338)$$

$$= \frac{g_{i\mathbf{k}}(\omega_{\mathbf{k}}) \left( 1 - \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} (2\varepsilon_i(t) + 2R_i - \varepsilon(t)) \right) + 2 \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} \frac{v_{i'\mathbf{k}}(\omega_{\mathbf{k}})}{\omega_{\mathbf{k}}} |B_{10}|^2 |V_{10}(t)|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{1 - \frac{\tanh\left(\frac{\beta\eta(t)}{2}\right)}{\eta(t)} \left( \varepsilon(t) - 2(\varepsilon(t) - \varepsilon_i(t) - R_i) - \frac{2|V_{10}(t)|^2 |B_{10}|^2 \coth\left(\frac{\beta\omega_{\mathbf{k}}}{2}\right)}{\omega_{\mathbf{k}}} \right)}. \quad (339)$$

#### IV. MASTER EQUATION

In order to describe the dynamics of the QD under the influence of the phonon environment, we use the time-convolutionless projection operator technique. The initial density operator is  $\rho_T(0) = \rho_S(0) \otimes \rho_B^{\text{Thermal}}$ , where  $\rho_B^{\text{Thermal}} \equiv \rho_B(0) \equiv \rho_B$ , so the transformed density operator is equal to:

$$\overline{\rho_T(0)} \equiv e^V \rho_T(0) e^{-V} \quad (340)$$

$$= (|0\rangle\langle 0|B_0^+ + |1\rangle\langle 1|B_1^+) (\rho_S(0) \otimes \rho_B) (|0\rangle\langle 0|B_0^- + |1\rangle\langle 1|B_1^-), \quad (341)$$

$$\text{for } \rho_S(0) = |0\rangle\langle 0|: |0\rangle\langle 0|B_0^+|0\rangle\langle 0|\rho_B|0\rangle\langle 0|B_0^- \quad (342)$$

$$= |0\rangle\langle 0|B_0^+|0\rangle\langle 0|\rho_B|0\rangle\langle 0|B_0^- \quad (343)$$

$$= |0\rangle\langle 0| \otimes B_0^+ \rho_B B_0^-, \quad (344)$$

$$\text{for } \rho_S(0) = |1\rangle\langle 1|: |1\rangle\langle 1|B_1^+|1\rangle\langle 1|\rho_B|1\rangle\langle 1|B_1^- \quad (345)$$

$$= |1\rangle\langle 1|B_1^+ \rho_B B_1^- \quad (346)$$

$$= |1\rangle\langle 1| \otimes B_1^+ \rho_B B_1^-, \quad (347)$$

$$\text{for } \rho_S(0) = |0\rangle\langle 1|: |0\rangle\langle 0|B_0^+|0\rangle\langle 1|\rho_B|1\rangle\langle 1|B_1^- \quad (348)$$

$$= |0\rangle\langle 1|B_0^+ \rho_B |1\rangle\langle 1|B_1^- \quad (349)$$

$$= |0\rangle\langle 1|1\rangle\langle 1|B_0^+ \rho_B B_1^- \quad (350)$$

$$= |0\rangle\langle 1| \otimes B_0^+ \rho_B B_1^-, \quad (351)$$

$$\text{for } \rho_S(0) = |1\rangle\langle 0|: |1\rangle\langle 1|B_1^+|1\rangle\langle 0|\rho_B|0\rangle\langle 0|B_0^- \quad (352)$$

$$= |1\rangle\langle 0| \otimes B_1^+ \rho_B B_0^-. \quad (353)$$

We transform any operator  $O$  into the interaction picture in the following way:

$$\tilde{O}(t) \equiv U^\dagger(t) O(t) U(t), \quad (354)$$

$$U(t) \equiv \mathcal{T} \exp \left( -i \int_0^t dt' \overline{H_S}(t') \right). \quad (355)$$

Here  $\mathcal{T}$  denotes a time ordering operator. Therefore:

$$\widetilde{\overline{\rho_S}}(t) = U^\dagger(t) \overline{\rho_S}(t) U(t), \text{ where} \quad (356)$$

$$\overline{\rho_S}(t) = \text{Tr}_B(\tilde{\rho}_T(t)). \quad (357)$$

. In order to separate the Hamiltonian we define the matrix  $\Lambda(t)$  such that  $\Lambda_{1i}(t) = A_i$ ,  $\Lambda_{2i}(t) = B_i$  and  $\Lambda_{3i}(t) = C_i(t)$  written as:

$$\begin{pmatrix} A(t) \\ B(t) \\ C(t) \end{pmatrix} = \begin{pmatrix} \sigma_x & \sigma_y & \frac{I-\sigma_z}{2} & \sigma_x & \sigma_y & \frac{I+\sigma_z}{2} \\ B_x & B_y & B_{1z} & B_y & B_x & B_{0z} \\ V_{10}^{\Re}(t) & V_{10}^{\Re}(t) & 1 & V_{10}^{\Im}(t) & -V_{10}^{\Im}(t) & 1 \end{pmatrix}. \quad (358)$$

In this case  $|1\rangle\langle 1| = \frac{I-\sigma_z}{2}$  and  $|0\rangle\langle 0| = \frac{I+\sigma_z}{2}$  with  $\sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} = |0\rangle\langle 0| - |1\rangle\langle 1|$ .

The previous notation allows us to write the interaction Hamiltonian  $\overline{H_I}(t)$  as pointed in the equation (236):

$$\overline{H_I}(t) = \sum_i B_{iz} |i\rangle\langle i| + V_{10}^{\Re}(t) (\sigma_x B_x + \sigma_y B_y) + V_{10}^{\Im}(t) (\sigma_x B_y - \sigma_y B_x) \quad (359)$$

$$= B_{0z} |0\rangle\langle 0| + B_{1z} |1\rangle\langle 1| + V_{10}^{\Re}(t) \sigma_x B_x + V_{10}^{\Re}(t) \sigma_y B_y + V_{10}^{\Im}(t) \sigma_x B_y - V_{10}^{\Im}(t) \sigma_y B_x \quad (360)$$

$$= \sum_i C_i(t) (A_i \otimes B_i(t)). \quad (361)$$

As the combined system and environment is closed, within the interaction picture the system-environment density operator evolves according to:



$$\frac{d\widetilde{\rho_T}(t)}{dt} = -i[\widetilde{H_I}(t), \widetilde{\rho_T}(t)]. \quad (362)$$

This equation has the formal solution

$$\widetilde{\rho_T}(t) = \overline{\rho_T}(0) - i \int_0^t [\widetilde{H_I}(s), \widetilde{\rho_T}(s)] ds. \quad (363)$$

Replacing the equation (363) in the equation (362) gives us:

$$\frac{d\widetilde{\rho_T}(t)}{dt} = -i[\widetilde{H_I}(t), \overline{\rho_T}(0)] - \int_0^t [\widetilde{H_I}(t), [\widetilde{H_I}(s), \widetilde{\rho_T}(s)]] ds. \quad (364)$$

This equation allow us to iterate and write in terms of a series expansion with  $\overline{\rho_T}(0)$  the solution as:

$$\widetilde{\rho_T}(t) = \overline{\rho_T}(0) + \sum_{n=0}^{\infty} (-i)^n \int_0^t dt_1 \int_0^{t_1} dt_2 \dots \int_0^{t_{n-1}} dt_n [\widetilde{H_I}(t_1), [\widetilde{H_I}(t_2), \dots [\widetilde{H_I}(t_n), \overline{\rho_T}(0)]] \dots]. \quad (365)$$

Taking the trace over the environmental degrees of freedom, we find

$$\widetilde{\rho_S}(t) = \overline{\rho_S}(0) + \sum_{n=1}^{\infty} (-i)^n \int_0^t dt_1 \int_0^{t_1} dt_2 \dots \int_0^{t_{n-1}} dt_n \text{Tr}_B [\widetilde{H_I}(t_1), [\widetilde{H_I}(t_2), \dots [\widetilde{H_I}(t_n), \overline{\rho_S}(0) \rho_B]] \dots]. \quad (366)$$

here we have assumed that  $\overline{\rho_T}(0) = \overline{\rho_S}(0) \otimes \rho_B$ . Consider the following notation:

$$\widetilde{\rho_S}(t) = (1 + W_1(t) + W_2(t) + \dots) \overline{\rho_S}(0) \quad (367)$$

$$= W(t) \overline{\rho_S}(0). \quad (368)$$

in this case

$$W_n(t) = (-i)^n \int_0^t dt_1 \int_0^{t_1} dt_2 \dots \int_0^{t_{n-1}} dt_n \text{Tr}_B [\widetilde{H_I}(t_1), [\widetilde{H_I}(t_2), \dots [\widetilde{H_I}(t_n), (\cdot) \rho_B]] \dots]. \quad (369)$$

are superoperators acting on the initial system density operator. Differentiating with respect to time, we have:

$$\frac{d\widetilde{\rho_S}(t)}{dt} = (\dot{W}_1(t) + \dot{W}_2(t) + \dots) \overline{\rho_S}(0) \quad (370)$$

$$= (\dot{W}_1(t) + \dot{W}_2(t) + \dots) W(t)^{-1} W(t) \overline{\rho_S}(0) \quad (371)$$

$$= (\dot{W}_1(t) + \dot{W}_2(t) + \dots) W(t)^{-1} \widetilde{\rho_S}(t). \quad (372)$$

where we assumed that  $W(t)$  is invertible. Usually, it is convenient (and possible) to define the interaction Hamiltonian such that  $\text{Tr}_B [\widetilde{H_I}(t) \rho_B] = 0$  so  $W_1(t) = 0$ . Thus, to second order and approximating  $W(t) \approx \mathbb{I}$  then the equation (370) becomes:

$$\frac{d\widetilde{\rho_S}(t)}{dt} = \dot{W}_2(t) \widetilde{\rho_S}(t) \quad (373)$$

$$= - \int_0^t dt_1 \text{Tr}_B [\widetilde{H_I}(t), [\widetilde{H_I}(t_1), \widetilde{\rho_S}(t) \rho_B]]. \quad (374)$$

Replacing  $t_1 \rightarrow t - \tau$

$$\frac{d\overline{\rho_S}(t)}{dt} = -i [\overline{H_S}(t), \overline{\rho_S}(t)] - \int_0^t d\tau \text{Tr}_B [\overline{H_I}(t), [\widetilde{\overline{H_I}}(-\tau), \overline{\rho_S}(t) \rho_B]] . \quad (375)$$

From the interaction picture applied on  $\overline{H_I}(t)$  we find:

$$\widetilde{\overline{H_I}}(t) = U^\dagger(t) e^{iH_B t} \overline{H_I}(t) e^{-iH_B t} U(t) . \quad (376)$$

we use the time-ordering operator  $\mathcal{T}$  because in general  $\overline{H_S}(t)$  doesn't commute with itself at two different times. We write the interaction Hamiltonian as:

$$\widetilde{\overline{H_I}}(t) = \sum_i C_i(t) (\widetilde{A_i}(t) \otimes \widetilde{B_i}(t)) , \quad (377)$$

$$\widetilde{A_i}(t) = U^\dagger(t) e^{iH_B t} A_i e^{-iH_B t} U(t) \quad (378)$$

$$= U^\dagger(t) A_i U(t) e^{iH_B t} e^{-iH_B t} \quad (379)$$

$$= U^\dagger(t) A_i U(t) \mathbb{I} \quad (380)$$

$$= U^\dagger(t) A_i U(t) , \quad (381)$$

$$\widetilde{B_i}(t) = U^\dagger(t) e^{iH_B t} B_i(t) e^{-iH_B t} U(t) \quad (382)$$

$$= U^\dagger(t) U(t) e^{iH_B t} B_i(t) e^{-iH_B t} \quad (383)$$

$$= \mathbb{I} e^{iH_B t} B_i(t) e^{-iH_B t} \quad (384)$$

$$= e^{iH_B t} B_i(t) e^{-iH_B t} . \quad (385)$$

Here we have used the fact that  $[\overline{H_S}(t), H_B] = 0$  because these operators belong to different Hilbert spaces, so  $[U(t), e^{iH_B t}] = 0$ .

Using the expression (377) to replace it in the equation (374)

$$\frac{d\widetilde{\overline{\rho_S}}(t)}{dt} = - \int_0^t \text{Tr}_B [\widetilde{\overline{H_I}}(t), [\widetilde{\overline{H_I}}(s), \widetilde{\overline{\rho_S}}(t) \rho_B]] ds \quad (386)$$

$$= - \int_0^t \text{Tr}_B \left[ \sum_j C_j(t) (\widetilde{A_j}(t) \otimes \widetilde{B_j}(t)) , \left[ \sum_i C_i(s) (\widetilde{A_i}(s) \otimes \widetilde{B_i}(s)) , \widetilde{\overline{\rho_S}}(t) \rho_B \right] \right] ds \quad (387)$$

$$= - \int_0^t \text{Tr}_B \left[ \sum_j C_j(t) (\widetilde{A_j}(t) \otimes \widetilde{B_j}(t)) , \sum_i C_i(s) (\widetilde{A_i}(s) \otimes \widetilde{B_i}(s)) \widetilde{\overline{\rho_S}}(t) \rho_B - \widetilde{\overline{\rho_S}}(t) \rho_B \sum_i C_i(s) (\widetilde{A_i}(s) \otimes \widetilde{B_i}(s)) \right] ds \quad (388)$$

$$= - \int_0^t \text{Tr}_B \left( \sum_j C_j(t) (\widetilde{A_j}(t) \otimes \widetilde{B_j}(t)) \sum_i C_i(s) (\widetilde{A_i}(s) \otimes \widetilde{B_i}(s)) \widetilde{\overline{\rho_S}}(t) \rho_B - \sum_j C_j(t) (\widetilde{A_j}(t) \otimes \widetilde{B_j}(t)) \widetilde{\overline{\rho_S}}(t) \rho_B \sum_i C_i(s) (\widetilde{A_i}(s) \otimes \widetilde{B_i}(s)) \right) \quad (389)$$

$$- \sum_i C_i(s) (\widetilde{A_i}(s) \otimes \widetilde{B_i}(s)) \widetilde{\overline{\rho_S}}(t) \rho_B \sum_j C_j(t) (\widetilde{A_j}(t) \otimes \widetilde{B_j}(t)) + \widetilde{\overline{\rho_S}}(t) \rho_B \sum_i C_i(s) (\widetilde{A_i}(s) \otimes \widetilde{B_i}(s)) \sum_j C_j(t) (\widetilde{A_j}(t) \otimes \widetilde{B_j}(t)) ) ds . \quad (390)$$

In order to calculate the correlation functions we define:

$$\mathcal{B}_{ij}(t, s) = \text{Tr}_B (\widetilde{B_i}(t) \widetilde{B_j}(s) \rho_B) \quad (391)$$

An useful property

$$\mathcal{B}_{ji}^*(t, s) = \text{Tr}_B \left( \widetilde{B}_j(t) \widetilde{B}_i(s) \rho_B \right)^\dagger \quad (392)$$

$$= \text{Tr}_B \left( \rho_B^\dagger \widetilde{B}_i^\dagger(s) \widetilde{B}_j^\dagger(t) \right) \quad (393)$$

$$= \text{Tr}_B \left( \rho_B \widetilde{B}_i(s) \widetilde{B}_j(t) \right) \quad (394)$$

$$= \text{Tr}_B \left( \widetilde{B}_i(s) \widetilde{B}_j(t) \rho_B \right) \quad (395)$$

$$= \mathcal{B}_{ij}(s, t) \quad (396)$$

The correlation functions relevant that appear in the equation (390) are:

$$\text{Tr}_B \left( \widetilde{B}_j(t) \widetilde{B}_i(s) \rho_B \right) = \left\langle \widetilde{B}_j(t) \widetilde{B}_i(s) \right\rangle_B \quad (397)$$

$$= \mathcal{B}_{ji}(t, s) \quad (398)$$

$$= \mathcal{B}_{ij}^*(s, t) \quad (399)$$

$$\text{Tr}_B \left( \widetilde{B}_j(t) \rho_B \widetilde{B}_i(s) \right) = \text{Tr}_B \left( \widetilde{B}_i(s) \widetilde{B}_j(t) \rho_B \right) \quad (400)$$

$$= \mathcal{B}_{ij}(s, t) \quad (401)$$

$$\text{Tr}_B \left( \widetilde{B}_i(s) \rho_B \widetilde{B}_j(t) \right) = \text{Tr}_B \left( \widetilde{B}_j(t) \widetilde{B}_i(s) \rho_B \right) \quad (402)$$

$$= \mathcal{B}_{ij}^*(s, t) \quad (403)$$

$$\text{Tr}_B \left( \rho_B \widetilde{B}_i(s) \widetilde{B}_j(t) \right) = \text{Tr}_B \left( \widetilde{B}_i(s) \widetilde{B}_j(t) \rho_B \right) \quad (404)$$

$$= \mathcal{B}_{ij}(s, t) \quad (405)$$

The cyclic property of the trace was use widely in the development of equations (397) and (405). Replacing in (390)

$$\frac{d\widetilde{\rho_S}(t)}{dt} = - \int_0^t \text{Tr}_B \left( \sum_j C_j(t) \left( \widetilde{A}_j(t) \otimes \widetilde{B}_j(t) \right) \sum_i C_i(s) \left( \widetilde{A}_i(s) \otimes \widetilde{B}_i(s) \right) \widetilde{\rho_S}(t) \rho_B - \sum_j C_j(t) \left( \widetilde{A}_j(t) \otimes \widetilde{B}_j(t) \right) \widetilde{\rho_S}(t) \rho_B \sum_i C_i(s) \left( \widetilde{A}_i(s) \otimes \widetilde{B}_i(s) \right) \right) ds \quad (406)$$

$$- \sum_i C_i(s) \left( \widetilde{A}_i(s) \otimes \widetilde{B}_i(s) \right) \widetilde{\rho_S}(t) \rho_B \sum_j C_j(t) \left( \widetilde{A}_j(t) \otimes \widetilde{B}_j(t) \right) + \widetilde{\rho_S}(t) \rho_B \sum_i C_i(s) \left( \widetilde{A}_i(s) \otimes \widetilde{B}_i(s) \right) \sum_j C_j(t) \left( \widetilde{A}_j(t) \otimes \widetilde{B}_j(t) \right) \Big) ds. \quad (407)$$

$$= - \int_0^t \text{Tr}_B \left( \sum_{ji} C_j(t) C_i(s) \left( \widetilde{A}_j(t) \widetilde{A}_i(s) \widetilde{\rho_S}(t) \widetilde{B}_j(t) \widetilde{B}_i(s) \rho_B - \widetilde{A}_j(t) \widetilde{\rho_S}(t) \widetilde{A}_i(s) \widetilde{B}_j(t) \rho_B \widetilde{B}_i(s) \right) \right) ds \quad (408)$$

$$+ \sum_{ij} C_i(s) C_j(t) \left( \widetilde{\rho_S}(t) \widetilde{A}_i(s) \widetilde{A}_j(t) \rho_B \widetilde{B}_i(s) \widetilde{B}_j(t) - \widetilde{A}_i(s) \widetilde{\rho_S}(t) \widetilde{A}_j(t) \widetilde{B}_i(s) \rho_B \widetilde{B}_j(t) \right) ds \quad (409)$$

$$= - \int_0^t \text{Tr}_B \left( \sum_{ji} C_j(t) C_i(s) \left( \widetilde{A}_j(t) \widetilde{A}_i(s) \widetilde{\rho_S}(t) \widetilde{B}_j(t) \widetilde{B}_i(s) \rho_B - \widetilde{A}_j(t) \widetilde{\rho_S}(t) \widetilde{A}_i(s) \widetilde{B}_j(t) \rho_B \widetilde{B}_i(s) \right) \right) ds \quad (410)$$

$$+ \sum_{ij} C_i(s) C_j(t) \left( \widetilde{\rho_S}(t) \widetilde{A}_i(s) \widetilde{A}_j(t) \rho_B \widetilde{B}_i(s) \widetilde{B}_j(t) - \widetilde{A}_i(s) \widetilde{\rho_S}(t) \widetilde{A}_j(t) \widetilde{B}_i(s) \rho_B \widetilde{B}_j(t) \right) ds \quad (411)$$

$$= - \int_0^t \text{Tr}_B \left( \sum_{ij} C_j(t) C_i(s) \left( \widetilde{A}_j(t) \widetilde{A}_i(s) \widetilde{\rho_S}(t) \widetilde{B}_j(t) \widetilde{B}_i(s) \rho_B - \widetilde{A}_j(t) \widetilde{\rho_S}(t) \widetilde{A}_i(s) \widetilde{B}_j(t) \rho_B \widetilde{B}_i(s) \right) \right) ds \quad (412)$$

$$+ \sum_{ij} C_i(s) C_j(t) \left( \widetilde{\rho_S}(t) \widetilde{A}_i(s) \widetilde{A}_j(t) \rho_B \widetilde{B}_i(s) \widetilde{B}_j(t) - \widetilde{A}_i(s) \widetilde{\rho_S}(t) \widetilde{A}_j(t) \widetilde{B}_i(s) \rho_B \widetilde{B}_j(t) \right) ds \quad (413)$$

$$= - \int_0^t \text{Tr}_B \left( \sum_{ij} C_j(t) C_i(s) \left( \widetilde{A}_j(t) \widetilde{A}_i(s) \widetilde{\rho_S}(t) \widetilde{B}_j(t) \widetilde{B}_i(s) \rho_B - \widetilde{A}_j(t) \widetilde{\rho_S}(t) \widetilde{A}_i(s) \widetilde{B}_j(t) \rho_B \widetilde{B}_i(s) \right) \right) ds \quad (414)$$

$$+ \widetilde{\rho_S}(t) \widetilde{A}_i(s) \widetilde{A}_j(t) \rho_B \widetilde{B}_i(s) \widetilde{B}_j(t) - \widetilde{A}_i(s) \widetilde{\rho_S}(t) \widetilde{A}_j(t) \widetilde{B}_i(s) \rho_B \widetilde{B}_j(t) \Big) ds \quad (415)$$

$$= - \int_0^t \left( \sum_{ij} C_j(t) C_i(s) \left( \widetilde{A}_j(t) \widetilde{A}_i(s) \widetilde{\rho_S}(t) \mathcal{B}_{ji}(t, s) - \widetilde{A}_j(t) \widetilde{\rho_S}(t) \widetilde{A}_i(s) \mathcal{B}_{ij}(s, t) \right) \right) ds \quad (416)$$

$$+ \widetilde{\rho_S}(t) \widetilde{A}_i(s) \widetilde{A}_j(t) \mathcal{B}_{ij}(s, t) - \widetilde{A}_i(s) \widetilde{\rho_S}(t) \widetilde{A}_j(t) \mathcal{B}_{ji}(t, s) \Big) ds \quad (417)$$

$$= - \int_0^t \left( \sum_{ij} C_j(t) C_i(s) \left( \mathcal{B}_{ji}(t, s) \left[ \widetilde{A}_j(t), \widetilde{A}_i(s) \widetilde{\rho_S}(t) \right] + \mathcal{B}_{ij}(s, t) \left[ \widetilde{\rho_S}(t) \widetilde{A}_i(s), \widetilde{A}_j(t) \right] \right) \right) ds \quad (418)$$

$$= - \int_0^t \left( \sum_{ij} C_i(t) C_j(s) \left( \mathcal{B}_{ij}(t, s) \left[ \widetilde{A}_i(t), \widetilde{A}_j(s) \widetilde{\rho_S}(t) \right] + \mathcal{B}_{ji}(s, t) \left[ \widetilde{\rho_S}(t) \widetilde{A}_j(s), \widetilde{A}_i(t) \right] \right) \right) ds \quad (419)$$

$$= - \int_0^t \left( \sum_{ij} C_i(t) C_j(s) \left( \mathcal{B}_{ij}(t, s) \left[ \widetilde{A}_i(t), \widetilde{A}_j(s) \widetilde{\rho_S}(t) \right] + \mathcal{B}_{ij}^*(t, s) \left[ \widetilde{\rho_S}(t) \widetilde{A}_j(s), \widetilde{A}_i(t) \right] \right) \right) ds \quad (420)$$

$$= - \int_0^t \left( \sum_{ij} C_i(t) C_j(s) \left( \mathcal{B}_{ij}(t, s) \left[ \widetilde{A}_i(t), \widetilde{A}_j(s) \widetilde{\rho_S}(t) \right] - \mathcal{B}_{ij}^*(t, s) \left[ \widetilde{A}_i(t), \widetilde{\rho_S}(t) \widetilde{A}_j(s) \right] \right) \right) ds \quad (421)$$

We could identify the following commutators in the equation deduced:

$$\mathcal{B}_{ij}(t, s) \widetilde{A}_i(t) \widetilde{A}_j(s) \widetilde{\rho_S}(t) - \mathcal{B}_{ij}(t, s) \widetilde{A}_j(s) \widetilde{\rho_S}(t) \widetilde{A}_i(t) = \mathcal{B}_{ij}(t, s) [\widetilde{A}_i(t), \widetilde{A}_j(s) \widetilde{\rho_S}(t)], \quad (422)$$

$$\mathcal{B}_{ij}^*(t, s) \widetilde{\rho_S}(t) \widetilde{A}_j(s) \widetilde{A}_i(t) - \mathcal{B}_{ij}^*(t, s) \widetilde{A}_i(t) \widetilde{\rho_S}(t) \widetilde{A}_j(s) = \mathcal{B}_{ij}^*(t, s) [\widetilde{\rho_S}(t) \widetilde{A}_j, \widetilde{A}_i(t)]. \quad (423)$$

Returning to the Schroedinger picture we have:

$$U(t) \widetilde{A}_i(t) \widetilde{A}_j(s) \widetilde{\rho_S}(t) U^\dagger(t) = U(t) \widetilde{A}_i(t) U^\dagger(t) U(t) \widetilde{A}_j(s) U^\dagger(t) U(t) \widetilde{\rho_S}(t) U^\dagger(t), \quad (424)$$

$$= \left( U(t) \widetilde{A}_i(t) U^\dagger(t) \right) \left( U(t) \widetilde{A}_j(s) U^\dagger(t) \right) \left( U(t) \widetilde{\rho_S}(t) U^\dagger(t) \right), \quad (425)$$

$$= A_i(t) \widetilde{A}_j(s, t) \widetilde{\rho_S}(t). \quad (426)$$

This procedure applying to the relevant commutators give us:

$$U(t) [\widetilde{A}_i(t), \widetilde{A}_j(s) \widetilde{\rho_S}(t)] U^\dagger(t) = \left( U(t) \widetilde{A}_i(t) \widetilde{A}_j(s) \widetilde{\rho_S}(t) U^\dagger(t) - U(t) \widetilde{A}_j(s) \widetilde{\rho_S}(t) \widetilde{A}_i(t) U^\dagger(t) \right) \quad (427)$$

$$= A_i(t) \widetilde{A}_j(s, t) \widetilde{\rho_S}(t) - \widetilde{A}_j(s, t) \widetilde{\rho_S}(t) A_i(t) \quad (428)$$

$$= [A_i(t), \widetilde{A}_j(s, t) \widetilde{\rho_S}(t)]. \quad (429)$$

Introducing this transformed commutators in the equation (421) allow us to obtain the master equation of the system written as an integro-differential equation with the correlation functions  $\mathcal{B}_{ij}(\tau)$  as defined before, this equations has the following form:

$$\frac{d\widetilde{\rho_S}(t)}{dt} = -i[\widetilde{H_S}(t), \widetilde{\rho_S}(t)] - \sum_{ij} \int_0^t ds C_i(t) C_j(s) \left( \mathcal{B}_{ij}(t, s) [A_i(t), \widetilde{A}_j(s, t) \widetilde{\rho_S}(t)] + \mathcal{B}_{ij}^*(t, s) [\widetilde{\rho_S}(t) \widetilde{A}_j(s, t), A_i(t)] \right) \quad (430)$$

$$s = t - \tau \text{ (Change of variables in the integration process)} \quad (431)$$

$$\frac{d\widetilde{\rho_S}(t)}{dt} = -i[\widetilde{H_S}(t), \widetilde{\rho_S}(t)] - \sum_{ij} \int_0^t d\tau C_i(t) C_j(t - \tau) \left( \mathcal{B}_{ij}(t, t - \tau) [A_i(t), \widetilde{A}_j(t - \tau, t) \widetilde{\rho_S}(t)] + \mathcal{B}_{ij}^*(t, t - \tau) [\widetilde{\rho_S}(t) \widetilde{A}_j(t - \tau, t), A_i(t)] \right) \quad (432)$$

where  $i, j \in \{1, 2, 3, 4, 5, 6\}$ .

Here  $\widetilde{A}_j(t - \tau, t) = U(t) U^\dagger(t - \tau) A_j(t) U(t - \tau) U^\dagger(t)$  where  $U(t)$  is given by (355). The equation obtained is a non-Markovian master equation which describes the QD exciton dynamics in the variational frame with a general time-dependent Hamiltonian, and valid at second order in  $H_I(t)$ .

Calculating the correlation functions allow us to obtain:

$$\langle \widetilde{B_{jz}}(\tau) \widetilde{B_{jz}}(0) \rangle_B = \text{Tr}_B \left( \widetilde{B_{jz}}(\tau) \widetilde{B_{jz}}(0) \rho_B \right) \quad (433)$$

$$= \int d^2 \alpha P(\alpha) \langle \alpha | \widetilde{B_{jz}}(\tau) \widetilde{B_{jz}}(0) | \alpha \rangle \quad (434)$$

$$= \frac{1}{\pi N} \int \exp \left( -\frac{|\alpha|^2}{N} \right) \langle \alpha | \widetilde{B_{jz}}(\tau) \widetilde{B_{jz}}(0) | \alpha \rangle d^2 \alpha \quad (435)$$

$$= \frac{1}{\pi N} \int \exp \left( -\frac{|\alpha|^2}{N} \right) \langle \alpha | \widetilde{B_{jz}}(\tau) \widetilde{B_{jz}}(0) | \alpha \rangle d^2 \alpha, \quad (436)$$

$$\widetilde{B_{jz}}(\tau) = \sum_{\mathbf{k}} \left( (g_{j\mathbf{k}} - v_{j\mathbf{k}}) b_{\mathbf{k}}^\dagger e^{i\omega_{\mathbf{k}}\tau} + (g_{j\mathbf{k}} - v_{j\mathbf{k}})^* b_{\mathbf{k}} e^{-i\omega_{\mathbf{k}}\tau} \right), \quad (437)$$

$$\widetilde{B_{jz}}(0) = \sum_{\mathbf{k}'} \left( (g_{j\mathbf{k}'} - v_{j\mathbf{k}'}) b_{\mathbf{k}'}^\dagger + (g_{j\mathbf{k}'} - v_{j\mathbf{k}'})^* b_{\mathbf{k}'} \right), \quad (438)$$

$$\langle \widetilde{B_{jz}}(\tau) \widetilde{B_{jz}}(0) \rangle_B = \text{Tr}_B \left( \widetilde{B_{jz}}(\tau) \widetilde{B_{jz}}(0) \rho_B \right) \quad (439)$$

$$= \text{Tr}_B \left( \sum_{\mathbf{k}} \left( (g_{j\mathbf{k}} - v_{j\mathbf{k}}) b_{\mathbf{k}}^\dagger e^{i\omega_{\mathbf{k}}\tau} + (g_{j\mathbf{k}} - v_{j\mathbf{k}})^* b_{\mathbf{k}} e^{-i\omega_{\mathbf{k}}\tau} \right) \sum_{\mathbf{k}'} \left( (g_{j\mathbf{k}'} - v_{j\mathbf{k}'}) b_{\mathbf{k}'}^\dagger + (g_{j\mathbf{k}'} - v_{j\mathbf{k}'})^* b_{\mathbf{k}'} \right) \rho_B \right) \quad (440)$$

$$= \text{Tr}_B \left( \sum_{\mathbf{k} \neq \mathbf{k}'} \left( (g_{j\mathbf{k}} - v_{j\mathbf{k}}) b_{\mathbf{k}}^\dagger e^{i\omega_{\mathbf{k}}\tau} + (g_{j\mathbf{k}} - v_{j\mathbf{k}})^* b_{\mathbf{k}} e^{-i\omega_{\mathbf{k}}\tau} \right) \left( (g_{j\mathbf{k}'} - v_{j\mathbf{k}'}) b_{\mathbf{k}'}^\dagger + (g_{j\mathbf{k}'} - v_{j\mathbf{k}'})^* b_{\mathbf{k}'} \right) \rho_B \right) \quad (441)$$

$$+ \text{Tr}_B \left( \sum_{\mathbf{k}} \left( (g_{j\mathbf{k}} - v_{j\mathbf{k}}) b_{\mathbf{k}}^\dagger e^{i\omega_{\mathbf{k}}\tau} + (g_{j\mathbf{k}} - v_{j\mathbf{k}})^* b_{\mathbf{k}} e^{-i\omega_{\mathbf{k}}\tau} \right) \left( (g_{j\mathbf{k}} - v_{j\mathbf{k}}) b_{\mathbf{k}}^\dagger + (g_{j\mathbf{k}} - v_{j\mathbf{k}})^* b_{\mathbf{k}} \right) \rho_B \right), \quad (442)$$

$$g_{j\mathbf{k}} - v_{j\mathbf{k}} = p_{j\mathbf{k}} \quad (443)$$

$$\langle \widetilde{B_{jz}}(\tau) \widetilde{B_{jz}}(0) \rangle_B = \text{Tr}_B \left( \sum_{\mathbf{k} \neq \mathbf{k}'} \left( p_{j\mathbf{k}} b_{\mathbf{k}}^\dagger e^{i\omega_{\mathbf{k}}\tau} + p_{j\mathbf{k}}^* b_{\mathbf{k}} e^{-i\omega_{\mathbf{k}}\tau} \right) \left( p_{j\mathbf{k}'} b_{\mathbf{k}'}^\dagger + p_{j\mathbf{k}'}^* b_{\mathbf{k}'} \right) \rho_B \right) \quad (444)$$

$$+ \text{Tr}_B \left( \sum_{\mathbf{k}} \left( p_{j\mathbf{k}} b_{\mathbf{k}}^\dagger e^{i\omega_{\mathbf{k}}\tau} + p_{j\mathbf{k}}^* b_{\mathbf{k}} e^{-i\omega_{\mathbf{k}}\tau} \right) \left( p_{j\mathbf{k}} b_{\mathbf{k}}^\dagger + p_{j\mathbf{k}}^* b_{\mathbf{k}} \right) \rho_B \right) \quad (445)$$



$$\langle \widetilde{B}_{jz}(\tau) \widetilde{B}_{jz(0)} \rangle_B = \sum_{\mathbf{k}} |p_{j\mathbf{k}}|^2 \left( e^{i\omega_{\mathbf{k}}\tau} \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle 0 | |\alpha_{\mathbf{k}}|^2 | 0 \rangle d^2\alpha_{\mathbf{k}} \right) + \sum_{\mathbf{k}} |p_{j\mathbf{k}}|^2 \left( e^{-i\omega_{\mathbf{k}}\tau} \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle 0 | |\alpha_{\mathbf{k}}|^2 | 0 \rangle d^2\alpha_{\mathbf{k}} \right) \quad (470)$$

$$+\sum_{\mathbf{k}}|p_{j\mathbf{k}}|^2\left(e^{-i\omega_{\mathbf{k}}\tau}\frac{1}{\pi N}\int\exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right)\langle 0|b_{\mathbf{k}}b_{\mathbf{k}}^\dagger|0\rangle d^2\alpha_{\mathbf{k}}\right) \quad (471)$$

$$= \sum_{\mathbf{k}} |p_{j\mathbf{k}}|^2 \left( e^{i\omega_{\mathbf{k}} \tau} \frac{1}{\pi N} \int \alpha_{\mathbf{k}} |^2 \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) d^2 \alpha_{\mathbf{k}} + e^{-i\omega_{\mathbf{k}} \tau} \frac{1}{\pi N} \int \alpha_{\mathbf{k}} |^2 \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) d^2 \alpha_{\mathbf{k}} + e^{-i\omega_{\mathbf{k}} \tau} \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) d^2 \alpha_{\mathbf{k}} \right) \quad (472)$$

$$= \sum_{\mathbf{k}} |p_{j\mathbf{k}}|^2 \left( (e^{i\omega_{\mathbf{k}}\tau} + e^{-i\omega_{\mathbf{k}}\tau}) \frac{1}{\pi N} \int |\alpha_{\mathbf{k}}|^2 \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) d^2\alpha_{\mathbf{k}} \right) + \sum_{\mathbf{k}} |p_{j\mathbf{k}}|^2 \left( e^{-i\omega_{\mathbf{k}}\tau} \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) d^2\alpha_{\mathbf{k}} \right), \quad (473)$$

$$\frac{1}{\pi N} \int |\alpha_{\mathbf{k}}|^2 \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) d^2 \alpha_{\mathbf{k}} = \frac{1}{\pi N} \int_0^{2\pi} \int_0^\infty r^2 \exp\left(-\frac{r^2}{N}\right) r dr d\theta \quad (474)$$

$$= \sum_{\mathbf{k}} |p_{j\mathbf{k}}|^2 (2 \cos(\omega_{\mathbf{k}} \tau) N) + \sum_{\mathbf{k}} |p_{j\mathbf{k}}|^2 e^{-i\omega_{\mathbf{k}} \tau} \quad (475)$$

$$= \sum_{\mathbf{k}} |p_{j\mathbf{k}}|^2 (2 \cos(\omega_{\mathbf{k}}\tau) N + e^{-i\omega_{\mathbf{k}}\tau}) \quad (476)$$

$$= \sum_{\mathbf{k}} |p_{j\mathbf{k}}|^2 \left( \frac{2 \cos(\omega_{\mathbf{k}} \tau)}{e^{\beta \omega_{\mathbf{k}}} - 1} + e^{-i \omega_{\mathbf{k}} \tau} \right) \quad (477)$$

$$= \sum_{\mathbf{k}} |p_{j\mathbf{k}}|^2 \left( \frac{2 \cos(\omega_{\mathbf{k}}\tau)}{e^{\beta\omega_{\mathbf{k}}} - 1} + \cos(\omega_{\mathbf{k}}\tau) - i \sin(\omega_{\mathbf{k}}\tau) \right) \quad (478)$$

$$= \sum_{\mathbf{k}} |p_{j\mathbf{k}}|^2 \left( \frac{(2 + e^{\beta\omega_{\mathbf{k}}} - 1) \cos(\omega_{\mathbf{k}}\tau)}{e^{\beta\omega_{\mathbf{k}}} - 1} - i \sin(\omega_{\mathbf{k}}\tau) \right) \quad (479)$$

$$= \sum_{\mathbf{k}} |p_{j\mathbf{k}}|^2 \left( \frac{(1 + e^{\beta\omega_{\mathbf{k}}}) \cos(\omega_{\mathbf{k}}\tau)}{e^{\beta\omega_{\mathbf{k}}} - 1} - i \sin(\omega_{\mathbf{k}}\tau) \right) \quad (480)$$

$$= \sum_{\mathbf{k}} |p_{j\mathbf{k}}|^2 \left( \frac{\left( e^{-\frac{\beta\omega_{\mathbf{k}}}{2}} + e^{\frac{\beta\omega_{\mathbf{k}}}{2}} \right) \cos(\omega_{\mathbf{k}}\tau)}{e^{-\frac{\beta\omega_{\mathbf{k}}}{2}} - e^{\frac{\beta\omega_{\mathbf{k}}}{2}}} - i \sin(\omega_{\mathbf{k}}\tau) \right) \quad (481)$$

$$= \sum_{\mathbf{k}} |p_{j\mathbf{k}}|^2 \left( \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \cos(\omega_{\mathbf{k}} \tau) - i \sin(\omega_{\mathbf{k}} \tau) \right) \quad (482)$$

$$= \sum_{\mathbf{k}} |g_{j\mathbf{k}} - v_{j\mathbf{k}}|^2 \left( \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \cos(\omega_{\mathbf{k}} \tau) - i \sin(\omega_{\mathbf{k}} \tau) \right), \quad (483)$$

$$\langle \widetilde{B_{jz}}(\tau) \widetilde{B_{j'z}}(0) \rangle_B = \int d^2 \alpha_{\mathbf{k}} P(\alpha_{\mathbf{k}}) \langle \alpha_{\mathbf{k}} | \widetilde{B_{jz}}(\tau) \widetilde{B_{j'z}}(0) | \alpha_{\mathbf{k}} \rangle \quad (484)$$

$$= \frac{1}{\pi N} \int \exp \left( -\frac{|\alpha_{\mathbf{k}}|^2}{N} \right) \left\langle \alpha_{\mathbf{k}} \left| \widetilde{B}_{jz}(\tau) \widetilde{B}_{j'z}(0) \right| \alpha_{\mathbf{k}} \right\rangle d^2 \alpha_{\mathbf{k}} \quad (485)$$

$$= \frac{1}{\pi N} \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle \alpha_{\mathbf{k}} | \sum_{\mathbf{k}} \left( (g_{j\mathbf{k}} - v_{j\mathbf{k}}) b_{\mathbf{k}}^\dagger e^{i\omega_{\mathbf{k}}\tau} + (g_{j\mathbf{k}} - v_{j\mathbf{k}})^* b_{\mathbf{k}} e^{-i\omega_{\mathbf{k}}\tau} \right) \sum_{\mathbf{k}'} \left( (g_{j'\mathbf{k}'} - v_{j'\mathbf{k}'}) b_{\mathbf{k}'}^\dagger + (g_{j'\mathbf{k}'} - v_{j'\mathbf{k}'})^* b_{\mathbf{k}'} \right) | \alpha_{\mathbf{k}} \rangle d^2 \alpha_{\mathbf{k}} \quad (486)$$

$$= \frac{1}{\pi N} \exp\left(-\frac{|\alpha_k|^2}{N}\right) \langle \alpha_k | \sum_{k \neq k'} \left( (g_{jk} - v_{jk}) b_k^\dagger e^{i\omega_k \tau} + (g_{jk} - v_{jk})^* b_k e^{-i\omega_k \tau} \right) \left( (g_{j'k'} - v_{j'k'}) b_{k'}^\dagger + (g_{j'k'} - v_{j'k'})^* b_{k'} \right) | \alpha_k \rangle d^2 \alpha_k \quad (487)$$

$$+ \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle \alpha_{\mathbf{k}} | \sum_{\mathbf{k}} ((g_{j\mathbf{k}} - v_{j\mathbf{k}}) b_{\mathbf{k}}^\dagger e^{i\omega_{\mathbf{k}}\tau} + (g_{j\mathbf{k}} - v_{j\mathbf{k}})^* b_{\mathbf{k}} e^{-i\omega_{\mathbf{k}}\tau}) ((g'_{j'\mathbf{k}} - v_{j'\mathbf{k}}) b_{\mathbf{k}}^\dagger + (g'_{j'\mathbf{k}} - v_{j'\mathbf{k}})^* b_{\mathbf{k}}) | \alpha_{\mathbf{k}} \rangle d^2 \alpha_{\mathbf{k}} \quad (488)$$

$$= \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle \alpha_{\mathbf{k}} | \sum_{\mathbf{k}} \left( (g_{j\mathbf{k}} - v_{j\mathbf{k}}) b_{\mathbf{k}}^\dagger e^{i\omega_{\mathbf{k}}\tau} + (g_{j\mathbf{k}} - v_{j\mathbf{k}})^* b_{\mathbf{k}} e^{-i\omega_{\mathbf{k}}\tau} \right) \left( (g_{j'\mathbf{k}} - v_{j'\mathbf{k}}) b_{\mathbf{k}}^\dagger + (g_{j'\mathbf{k}} - v_{j'\mathbf{k}})^* b_{\mathbf{k}} \right) | \alpha_{\mathbf{k}} \rangle d^2 \alpha_{\mathbf{k}} \quad (489)$$

$$= \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \left\langle \alpha_{\mathbf{k}} \left| \sum_{\mathbf{k}} (g_{j\mathbf{k}} - v_{j\mathbf{k}}) (g_{j'\mathbf{k}} - v_{j'\mathbf{k}})^* b_{\mathbf{k}}^\dagger b_{\mathbf{k}} e^{i\omega_{\mathbf{k}}\tau} \right| \alpha_{\mathbf{k}} \right\rangle d^2\alpha_{\mathbf{k}} \quad (490)$$

$$+ \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \left\langle \alpha_{\mathbf{k}} \left| \sum_{\mathbf{k}} (g_{j\mathbf{k}} - v_{j\mathbf{k}})^* (g_{j'\mathbf{k}} - v_{j'\mathbf{k}}) b_{\mathbf{k}} b_{\mathbf{k}}^\dagger e^{-i\omega_{\mathbf{k}}\tau} \right| \alpha_{\mathbf{k}} \right\rangle d^2\alpha_{\mathbf{k}} \quad (491)$$

$$= \sum_{\mathbf{k}} (g_{j\mathbf{k}} - v_{j\mathbf{k}}) (g_{j'\mathbf{k}} - v_{j'\mathbf{k}})^* e^{i\omega_{\mathbf{k}}\tau} \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle \alpha_{\mathbf{k}} | b_{\mathbf{k}}^\dagger b_{\mathbf{k}} | \alpha_{\mathbf{k}} \rangle d^2 \alpha_{\mathbf{k}} \quad (492)$$

$$+ \sum_{\mathbf{k}} (g_{j\mathbf{k}} - v_{j\mathbf{k}})^* (g_{j'\mathbf{k}} - v_{j'\mathbf{k}}) e^{-i\omega_{\mathbf{k}}\tau} \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle \alpha_{\mathbf{k}} | b_{\mathbf{k}} b_{\mathbf{k}}^\dagger | \alpha_{\mathbf{k}} \rangle d^2\alpha_{\mathbf{k}}, \quad (493)$$

$$\frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle \alpha_{\mathbf{k}} | b_{\mathbf{k}}^\dagger b_{\mathbf{k}} | \alpha_{\mathbf{k}} \rangle d^2 \alpha_{\mathbf{k}} = \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle 0 | D(-\alpha_{\mathbf{k}}) b_{\mathbf{k}}^\dagger D(\alpha_{\mathbf{k}}) D(-\alpha_{\mathbf{k}}) b_{\mathbf{k}} D(\alpha_{\mathbf{k}}) | 0 \rangle d^2 \alpha_{\mathbf{k}} \quad (494)$$

$$= \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle 0 | D(-\alpha_{\mathbf{k}}) b_{\mathbf{k}}^\dagger D(\alpha_{\mathbf{k}}) D(-\alpha_{\mathbf{k}}) b_{\mathbf{k}} D(\alpha_{\mathbf{k}}) | 0 \rangle d^2 \alpha_{\mathbf{k}} \quad (495)$$

$$= \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle 0 | (b_{\mathbf{k}}^\dagger + \alpha_{\mathbf{k}}^*) (b_{\mathbf{k}} + \alpha_{\mathbf{k}}) | 0 \rangle d^2 \alpha_{\mathbf{k}} \quad (496)$$

$$= \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) |\alpha_{\mathbf{k}}|^2 d^2 \alpha_{\mathbf{k}} \quad (497)$$

$$= N, \quad (498)$$

$$\frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle \alpha_{\mathbf{k}} | b_{\mathbf{k}} b_{\mathbf{k}}^\dagger | \alpha_{\mathbf{k}} \rangle d^2 \alpha_{\mathbf{k}} = \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle 0 | D(-\alpha_{\mathbf{k}}) b_{\mathbf{k}} D(\alpha_{\mathbf{k}}) D(-\alpha_{\mathbf{k}}) b_{\mathbf{k}}^\dagger D(\alpha_{\mathbf{k}}) | 0 \rangle d^2 \alpha_{\mathbf{k}} \quad (499)$$

$$= \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle 0 | (b_{\mathbf{k}} + \alpha_{\mathbf{k}}) (b_{\mathbf{k}}^\dagger + \alpha_{\mathbf{k}}^*) | 0 \rangle d^2 \alpha_{\mathbf{k}} \quad (500)$$

$$= \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle 0 | b_{\mathbf{k}} b_{\mathbf{k}}^\dagger + \alpha_{\mathbf{k}} b_{\mathbf{k}}^\dagger + b_{\mathbf{k}} \alpha_{\mathbf{k}}^* + |\alpha_{\mathbf{k}}|^2 | 0 \rangle d^2 \alpha_{\mathbf{k}} \quad (501)$$

$$= \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle 0 | b_{\mathbf{k}} b_{\mathbf{k}}^\dagger + |\alpha_{\mathbf{k}}|^2 | 0 \rangle d^2 \alpha_{\mathbf{k}} \quad (502)$$

$$= \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle 0 | |\alpha_{\mathbf{k}}|^2 | 0 \rangle d^2 \alpha_{\mathbf{k}} + \frac{1}{\pi N} \int \exp\left(-\frac{|\alpha_{\mathbf{k}}|^2}{N}\right) \langle 0 | b_{\mathbf{k}} b_{\mathbf{k}}^\dagger | 0 \rangle d^2 \alpha_{\mathbf{k}} \quad (503)$$

$$= N + 1, \quad (504)$$

$$\langle \widetilde{B_{jz}}(\tau) \widetilde{B_{j'z}}(0) \rangle_B = \sum_{\mathbf{k}} (g_{j\mathbf{k}} - v_{j\mathbf{k}})(g_{j'\mathbf{k}} - v_{j'\mathbf{k}})^* e^{i\omega_{\mathbf{k}}\tau} N + \sum_{\mathbf{k}} (g_{j\mathbf{k}} - v_{j\mathbf{k}})^* (g_{j'\mathbf{k}} - v_{j'\mathbf{k}}) e^{-i\omega_{\mathbf{k}}\tau} (N + 1) \quad (505)$$

$$= \sum_{\mathbf{k}} (g_{j\mathbf{k}} - v_{j\mathbf{k}})^* (g_{j'\mathbf{k}} - v_{j'\mathbf{k}}) e^{-i\omega_{\mathbf{k}}\tau} + N ((g_{j\mathbf{k}} - v_{j\mathbf{k}})(g_{j'\mathbf{k}} - v_{j'\mathbf{k}})^* e^{i\omega_{\mathbf{k}}\tau} + (g_{j\mathbf{k}} - v_{j\mathbf{k}})^* (g_{j'\mathbf{k}} - v_{j'\mathbf{k}}) e^{-i\omega_{\mathbf{k}}\tau}), \quad (506)$$

$$D(h') D(h) = \exp\left(\frac{1}{2}(h'h^* - h'^*h)\right) D(h' + h), \quad (507)$$

$$\langle D(h') D(h) \rangle_B = \text{Tr}_B \left( \exp\left(\frac{1}{2}(h'h^* - h'^*h)\right) D(h' + h) \rho_B \right) \quad (508)$$

$$= \exp\left(\frac{1}{2}(h'h^* - h'^*h)\right) \text{Tr}_B (D(h' + h) \rho_B) \quad (509)$$

$$= \exp\left(\frac{1}{2}(h'h^* - h'^*h)\right) \frac{1}{\pi N} \int d^2 \alpha P(\alpha) \langle \alpha | D(h' + h) | \alpha \rangle \quad (510)$$

$$= \exp\left(\frac{1}{2}(h'h^* - h'^*h)\right) \exp\left(-\frac{|h + h'|^2}{2} \coth\left(\frac{\beta\omega}{2}\right)\right), \quad (511)$$

$$h' = h \exp(i\omega\tau), \quad (512)$$

$$\langle D(h \exp(i\omega\tau)) D(h) \rangle_B = \exp\left(\frac{1}{2}(hh^* \exp(i\omega\tau) - h^* h \exp(-i\omega\tau))\right) \exp\left(-\frac{|h + h \exp(i\omega\tau)|^2}{2} \coth\left(\frac{\beta\omega}{2}\right)\right), \quad (513)$$

$$\frac{1}{2}|h|^2(\exp(i\omega\tau) - \exp(-i\omega\tau)) = \frac{1}{2}(hh^* \exp(i\omega\tau) - h^* h \exp(-i\omega\tau)) \quad (514)$$

$$= \frac{1}{2}|h|^2(\cos(\omega\tau) + i \sin(\omega\tau) - \cos(\omega\tau) + i \sin(\omega\tau)) \quad (515)$$

$$= \frac{1}{2}|h|^2(2i \sin(\omega\tau)) \quad (516)$$

$$= i|h|^2 \sin(\omega\tau), \quad (517)$$

$$-\frac{|h + h \exp(i\omega\tau)|^2}{2} = -|h|^2 \frac{|1 + \exp(i\omega\tau)|^2}{2} \quad (518)$$

$$= -|h|^2 \frac{(1 + 2 \cos(\omega\tau) + \cos^2(\omega\tau)) + \sin^2(\omega\tau)}{2} \quad (519)$$





$$= \prod_{\mathbf{k}} \exp \left( - \left| \frac{v_{0\mathbf{k}} - v_{1\mathbf{k}}}{\omega_{\mathbf{k}}} \right|^2 \left( i \sin(\omega_{\mathbf{k}} \tau) - \cos(\omega_{\mathbf{k}} \tau) \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \right) \exp \left( - \left| \frac{v_{0\mathbf{k}} - v_{1\mathbf{k}}}{\omega_{\mathbf{k}}} \right|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right), \quad (545)$$

$$\left\langle \widetilde{B_0^+ B_1^-(\tau)} \widetilde{B_1^+ B_0^-(0)} \right\rangle_B = \text{Tr}_B \left( \Pi_{\mathbf{k}} \left( D \left( \frac{v_{0\mathbf{k}} - v_{1\mathbf{k}}}{\omega_{\mathbf{k}}} e^{i\omega_{\mathbf{k}} \tau} \right) e^{\frac{1}{2} \left( \frac{v_{0\mathbf{k}}^* v_{1\mathbf{k}} - v_{0\mathbf{k}} v_{1\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right)} \right) \Pi_{\mathbf{k}} \left( D \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right) e^{\frac{1}{2} \left( \frac{v_{1\mathbf{k}}^* v_{0\mathbf{k}} - v_{1\mathbf{k}} v_{0\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right)} \right) \rho_B \right) \quad (546)$$

$$= \text{Tr}_B \left( \prod_{\mathbf{k}} D \left( \frac{v_{0\mathbf{k}} - v_{1\mathbf{k}}}{\omega_{\mathbf{k}}} e^{i\omega_{\mathbf{k}} \tau} \right) \prod_{\mathbf{k}} D \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right) \rho_B \right) \quad (547)$$

$$= \prod_{\mathbf{k}} \text{Tr}_B \left( D \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} e^{i(\omega_{\mathbf{k}} \tau + \pi)} \right) D \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right) \rho_B \right) \quad (548)$$

$$= \prod_{\mathbf{k}} \exp \left( - \left| \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right|^2 \left( -i \sin(\omega_{\mathbf{k}} \tau + \pi) + \cos(\omega_{\mathbf{k}} \tau + \pi) \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \right) \exp \left( - \left| \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \quad (549)$$

$$= \left\langle \widetilde{B_1^+ B_0^-(\tau)} \widetilde{B_0^+ B_1^-(0)} \right\rangle_B, \quad (550)$$

$$\left\langle \widetilde{B_0^+ B_1^-(\tau)} \widetilde{B_{jz}^-(0)} \right\rangle_B = \text{Tr}_B \left( \Pi_{\mathbf{k}} \left( D \left( \frac{v_{0\mathbf{k}} - v_{1\mathbf{k}}}{\omega_{\mathbf{k}}} e^{i\omega_{\mathbf{k}} \tau} \right) e^{\frac{1}{2} \left( \frac{v_{0\mathbf{k}}^* v_{1\mathbf{k}} - v_{0\mathbf{k}} v_{1\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right)} \right) \Sigma_{\mathbf{k}'} \left( (g_{j\mathbf{k}'} - v_{j\mathbf{k}'}) b_{\mathbf{k}'}^\dagger + (g_{j\mathbf{k}'} - v_{j\mathbf{k}'})^* b_{\mathbf{k}'} \right) \rho_B \right), \quad (551)$$

$$\langle D(h) b \rangle_B = \frac{1}{\pi N} \int d^2 \alpha \exp \left( - \frac{|\alpha|^2}{2} \right) \langle \alpha | D(h) b | \alpha \rangle \quad (552)$$

$$= \frac{1}{\pi N} \int d^2 \alpha \exp \left( - \frac{|\alpha|^2}{2} \right) \langle \alpha | D(-\alpha) D(h) b D(\alpha) | \alpha \rangle \quad (553)$$

$$= \frac{1}{\pi N} \int d^2 \alpha \exp \left( - \frac{|\alpha|^2}{2} \right) \langle 0 | D(-\alpha) D(h) b D(\alpha) | 0 \rangle \quad (554)$$

$$= \frac{1}{\pi N} \int d^2 \alpha \exp \left( - \frac{|\alpha|^2}{2} \right) \langle 0 | D(-\alpha) D(h) D(\alpha) D(-\alpha) b D(\alpha) | 0 \rangle \quad (555)$$

$$= \frac{1}{\pi N} \int d^2 \alpha \exp \left( - \frac{|\alpha|^2}{2} \right) \langle 0 | D(-\alpha) D(h) D(\alpha) (b + \alpha) | 0 \rangle \quad (556)$$

$$= \frac{1}{\pi N} \int d^2 \alpha \exp \left( - \frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \langle 0 | D(h) (b + \alpha) | 0 \rangle \quad (557)$$

$$= \frac{1}{\pi N} \int d^2 \alpha \exp \left( - \frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \langle 0 | D(h) b | 0 \rangle + \frac{1}{\pi N} \int d^2 \alpha \exp \left( - \frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \langle 0 | D(h) \alpha | 0 \rangle \quad (558)$$

$$= \frac{1}{\pi N} \int d^2 \alpha \exp \left( - \frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \langle 0 | D(h) \alpha | 0 \rangle \quad (559)$$

$$= \frac{1}{\pi N} \int \alpha \exp \left( - \frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \exp \left( - \frac{|h|^2}{2} \right) d^2 \alpha \quad (560)$$

$$= hN \langle D(h) \rangle_B, \quad (561)$$

$$\langle D(h) b^\dagger \rangle_B = \frac{1}{\pi N} \int d^2 \alpha \exp \left( - \frac{|\alpha|^2}{2} \right) \langle \alpha | D(h) b^\dagger | \alpha \rangle \quad (562)$$

$$= \frac{1}{\pi N} \int d^2 \alpha \exp \left( - \frac{|\alpha|^2}{2} \right) \langle 0 | D(-\alpha) D(h) b^\dagger D(\alpha) | 0 \rangle \quad (563)$$

$$= \frac{1}{\pi N} \int d^2 \alpha \exp \left( - \frac{|\alpha|^2}{2} \right) \langle 0 | D(-\alpha) D(h) b^\dagger D(\alpha) | 0 \rangle \quad (564)$$

$$= \frac{1}{\pi N} \int d^2 \alpha \exp \left( - \frac{|\alpha|^2}{2} \right) \langle 0 | D(-\alpha) D(h) D(\alpha) D(-\alpha) b^\dagger D(\alpha) | 0 \rangle \quad (565)$$

$$= \frac{1}{\pi N} \int d^2 \alpha \exp \left( -\frac{|\alpha|^2}{2} \right) \langle 0 | D(-\alpha) D(h) D(\alpha) (b^\dagger + \alpha^*) | 0 \rangle \quad (566)$$

$$= \frac{1}{\pi N} \int d^2 \alpha \exp \left( -\frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \langle 0 | D(h) (b^\dagger + \alpha^*) | 0 \rangle \quad (567)$$

$$= \frac{1}{\pi N} \int d^2 \alpha \exp \left( -\frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \langle 0 | D(h) b^\dagger | 0 \rangle + \frac{1}{\pi N} \int d^2 \alpha \exp \left( -\frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \langle 0 | D(h) \alpha^* | 0 \rangle \quad (568)$$

$$= \frac{1}{\pi N} \int d^2 \alpha \exp \left( -\frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \langle 0 | D(h) | 1 \rangle + \frac{1}{\pi N} \int d^2 \alpha \exp \left( -\frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \alpha^* \langle 0 | D(h) | 0 \rangle \quad (569)$$

$$= \frac{1}{\pi N} \int d^2 \alpha \exp \left( -\frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \langle -h | 1 \rangle + \frac{1}{\pi N} \int d^2 \alpha \exp \left( -\frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \alpha^* \langle 0 | D(h) | 0 \rangle, \quad (570)$$

$$\langle -h | = \exp \left( -\frac{|-h^*|^2}{2} \right) \sum_n \frac{(-h^*)^n}{\sqrt{n!}} \langle n |, \quad (571)$$

$$\langle -h | 1 \rangle = \exp \left( -\frac{|-h^*|^2}{2} \right) (-h^*), \quad (572)$$

$$\langle D(h) b^\dagger \rangle_B = \frac{1}{\pi N} \int d^2 \alpha \exp \left( -\frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \exp \left( -\frac{|-h^*|^2}{2} \right) (-h^*) + \frac{1}{\pi N} \int d^2 \alpha \exp \left( -\frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \alpha^* \exp \left( -\frac{|-h^*|^2}{2} \right) \quad (573)$$

$$= -h^* \langle D(h) \rangle_B (N+1), \quad (574)$$

$$\langle b D(h) \rangle_B = \frac{1}{\pi N} \int d^2 \alpha \exp \left( -\frac{|\alpha|^2}{2} \right) \langle \alpha | b D(h) | \alpha \rangle \quad (575)$$

$$= \frac{1}{\pi N} \int d^2 \alpha \exp \left( -\frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \exp \left( -\frac{|h|^2}{2} \right) h + \frac{1}{\pi N} \int d^2 \alpha \exp \left( -\frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \alpha \exp \left( -\frac{|h|^2}{2} \right) \quad (576)$$

$$= h \langle D(h) \rangle_B (N+1), \quad (577)$$

$$\langle b^\dagger D(h) \rangle_B = \frac{1}{\pi N} \int d^2 \alpha \exp \left( -\frac{|\alpha|^2}{2} \right) \langle \alpha | b^\dagger D(h) | \alpha \rangle \quad (578)$$

$$= \frac{1}{\pi N} \int d^2 \alpha \exp \left( -\frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \exp \left( -\frac{|h|^2}{2} \right) h + \frac{1}{\pi N} \int d^2 \alpha \exp \left( -\frac{|\alpha|^2}{2} \right) \exp(h\alpha^* - h^* \alpha) \alpha \exp \left( -\frac{|h|^2}{2} \right) \quad (579)$$

$$= -h^* \langle D(h) \rangle_B N, \quad (580)$$

$$\left\langle \widetilde{B_1^+ B_0^-}(\tau) \right\rangle_B = \left\langle \prod_{\mathbf{k}} \left( D \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} e^{i\omega_{\mathbf{k}} \tau} \right) e^{\frac{1}{2} \left( \frac{v_{1\mathbf{k}}^* v_{0\mathbf{k}} - v_{1\mathbf{k}} v_{0\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right)} \right) \right\rangle_B \quad (581)$$

$$= \prod_{\mathbf{k}} \left( e^{\frac{1}{2} \left( \frac{v_{1\mathbf{k}}^* v_{0\mathbf{k}} - v_{1\mathbf{k}} v_{0\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right)} \right) \prod_{\mathbf{k}} \left\langle D \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} e^{i\omega_{\mathbf{k}} \tau} \right) \right\rangle_B \quad (582)$$

$$= \prod_{\mathbf{k}} \left( e^{\frac{1}{2} \left( \frac{v_{1\mathbf{k}}^* v_{0\mathbf{k}} - v_{1\mathbf{k}} v_{0\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right)} \right) \prod_{\mathbf{k}} \left\langle D \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} e^{i\omega_{\mathbf{k}} \tau} \right) \right\rangle_B \quad (583)$$

$$= \prod_{\mathbf{k}} \left( \exp \left( \frac{1}{2} \left( \frac{v_{1\mathbf{k}}^* v_{0\mathbf{k}} - v_{1\mathbf{k}} v_{0\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right) \right) \right) \prod_{\mathbf{k}} \exp \left( -\frac{1}{2} \left| \frac{v_{1\mathbf{k}}}{\omega_{\mathbf{k}}} - \frac{v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \quad (584)$$

$$= B_{10}. \quad (585)$$

The correlation functions can be found readily as:

$$\widetilde{B_1^+ B_0^-}(\tau) = \prod_{\mathbf{k}} \left( D \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} e^{i\omega_{\mathbf{k}} \tau} \right) \exp \left( \frac{1}{2} \left( \frac{v_{1\mathbf{k}}^* v_{0\mathbf{k}} - v_{1\mathbf{k}} v_{0\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right) \right) \right), \quad (586)$$

$$\widetilde{B_0^+ B_1^-}(\tau) = \prod_{\mathbf{k}} \left( D \left( \frac{v_{0\mathbf{k}} - v_{1\mathbf{k}}}{\omega_{\mathbf{k}}} e^{i\omega_{\mathbf{k}} \tau} \right) \exp \left( \frac{1}{2} \left( \frac{v_{0\mathbf{k}}^* v_{1\mathbf{k}} - v_{0\mathbf{k}} v_{1\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right) \right) \right), \quad (587)$$

$$\widetilde{B}_x(0) = \frac{B_1^+ B_0^- + B_0^+ B_1^- - B_{10} - B_{01}}{2}, \quad (588)$$

$$\widetilde{B}_y(0) = \frac{B_0^+ B_1^- - B_1^+ B_0^- + B_{10} - B_{01}}{2i}, \quad (589)$$

$$B_{10} = \left( \prod_{\mathbf{k}} \exp \left( \frac{1}{2} \left( \frac{v_{1\mathbf{k}}^* v_{0\mathbf{k}} - v_{1\mathbf{k}} v_{0\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right) \right) \right) \left( \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \left| \frac{v_{1\mathbf{k}}}{\omega_{\mathbf{k}}} - \frac{v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \right), \quad (590)$$

$$B_{iz} = \sum_{\mathbf{k}} \left( (g_{i\mathbf{k}} - v_{i\mathbf{k}}) b_{\mathbf{k}}^\dagger + (g_{i\mathbf{k}} - v_{i\mathbf{k}})^* b_{\mathbf{k}} \right), \quad (591)$$

$$\left\langle \widetilde{B}_{iz}(\tau) \widetilde{B}_{jz}(0) \right\rangle_B = \left\langle \sum_{\mathbf{k}} \left( (g_{i\mathbf{k}} - v_{i\mathbf{k}}) b_{\mathbf{k}}^\dagger e^{i\omega_{\mathbf{k}}\tau} + (g_{i\mathbf{k}} - v_{i\mathbf{k}})^* b_{\mathbf{k}} e^{-i\omega_{\mathbf{k}}\tau} \right) \sum_{\mathbf{k}} \left( (g_{j\mathbf{k}} - v_{j\mathbf{k}}) b_{\mathbf{k}}^\dagger + (g_{j\mathbf{k}} - v_{j\mathbf{k}})^* b_{\mathbf{k}} \right) \right\rangle_B \quad (592)$$

$$= \sum_{\mathbf{k}} (g_{i\mathbf{k}} - v_{i\mathbf{k}}) (g_{j\mathbf{k}} - v_{j\mathbf{k}})^* e^{i\omega_{\mathbf{k}}\tau} N_{\mathbf{k}} + \sum_{\mathbf{k}} (g_{i\mathbf{k}} - v_{i\mathbf{k}})^* (g_{j\mathbf{k}} - v_{j\mathbf{k}}) e^{-i\omega_{\mathbf{k}}\tau} (N_{\mathbf{k}} + 1), \quad (593)$$

$$\left\langle \widetilde{B}_x(\tau) \widetilde{B}_x(0) \right\rangle_B = \left\langle \frac{B_1^+ B_0^- (\tau) + B_0^+ B_1^- (\tau) - B_{10} - B_{01}}{2} \frac{B_1^+ B_0^- + B_0^+ B_1^- - B_{10} - B_{01}}{2} \right\rangle_B \quad (594)$$

$$= \frac{1}{4} \left\langle (B_1^+ B_0^- (\tau) + B_0^+ B_1^- (\tau) - B_{10} - B_{01}) (B_1^+ B_0^- + B_0^+ B_1^- - B_{10} - B_{01}) \right\rangle_B \quad (595)$$

$$= \frac{1}{4} \left\langle B_1^+ B_0^- (\tau) B_1^+ B_0^- + B_1^+ B_0^- (\tau) B_0^+ B_1^- - B_1^+ B_0^- (\tau) B_{10} - B_1^+ B_0^- (\tau) B_{01} + B_0^+ B_1^- (\tau) B_1^+ B_0^- + B_0^+ B_1^- (\tau) B_0^+ B_1^- \right. \quad (596)$$

$$\left. - B_0^+ B_1^- (\tau) B_{10} - B_0^+ B_1^- (\tau) B_{01} - B_{10} B_1^+ B_0^- - B_{10} B_0^+ B_1^- + B_{10} B_{10} + B_{10} B_{01} - B_{01} B_1^+ B_0^- - B_{01} B_0^+ B_1^- + B_{01} B_{10} + B_{01} B_{01} \right\rangle \quad (597)$$

$$= \frac{1}{4} \left\langle B_1^+ B_0^- (\tau) B_1^+ B_0^- + B_1^+ B_0^- (\tau) B_0^+ B_1^- - B_1^+ B_0^- (\tau) B_{10} - B_1^+ B_0^- (\tau) B_{01} + B_0^+ B_1^- (\tau) B_1^+ B_0^- \right. \quad (598)$$

$$\left. + B_0^+ B_1^- (\tau) B_0^+ B_1^- - B_0^+ B_1^- (\tau) B_{10} - B_0^+ B_1^- (\tau) B_{01} \right\rangle, \quad (599)$$

$$\left\langle \widetilde{B}_0^+ \widetilde{B}_1^- (\tau) \widetilde{B}_0^+ \widetilde{B}_1^- (0) \right\rangle_B = \Pi_{\mathbf{k}} \left( \exp \left( \frac{v_{0\mathbf{k}}^* v_{1\mathbf{k}} - v_{0\mathbf{k}} v_{1\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right) \exp \left( -\left| \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right|^2 \left( -i \sin(\omega_{\mathbf{k}}\tau) + \cos(\omega_{\mathbf{k}}\tau) \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \right) \exp \left( -\left| \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \right), \quad (600)$$

$$U = \prod_{\mathbf{k}} \left( \exp \left( \frac{v_{0\mathbf{k}}^* v_{1\mathbf{k}} - v_{0\mathbf{k}} v_{1\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right) \right), \quad (601)$$

$$\phi(\tau) = \sum_{\mathbf{k}} \left| \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right|^2 \left( -i \sin(\omega_{\mathbf{k}}\tau) + \cos(\omega_{\mathbf{k}}\tau) \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right), \quad (602)$$

$$S = \prod_{\mathbf{k}} \exp \left( -\left| \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right), \quad (603)$$

$$\left\langle \widetilde{B}_0^+ \widetilde{B}_1^- (\tau) \widetilde{B}_0^+ \widetilde{B}_1^- (0) \right\rangle_B = U \exp(-\phi(\tau)) S, \quad (604)$$

$$\left\langle \widetilde{B}_1^+ \widetilde{B}_0^- (\tau) \widetilde{B}_1^+ \widetilde{B}_0^- (0) \right\rangle_B = U^* \exp(-\phi(\tau)) S, \quad (605)$$

$$\left\langle \widetilde{B}_1^+ \widetilde{B}_0^- (\tau) \widetilde{B}_0^+ \widetilde{B}_1^- (0) \right\rangle_B = \exp(\phi(\tau)) S, \quad (606)$$

$$\left\langle \widetilde{B}_0^+ \widetilde{B}_1^- (\tau) \widetilde{B}_1^+ \widetilde{B}_0^- (0) \right\rangle_B = \left\langle \widetilde{B}_1^+ \widetilde{B}_0^- (\tau) \widetilde{B}_0^+ \widetilde{B}_1^- (0) \right\rangle_B, \quad (607)$$

$$\left\langle \widetilde{B}_1^+ \widetilde{B}_0^- (\tau) \right\rangle_B = \prod_{\mathbf{k}} \left( \exp \left( \frac{1}{2} \left( \frac{v_{1\mathbf{k}}^* v_{0\mathbf{k}} - v_{1\mathbf{k}} v_{0\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right) \right) \right) \prod_{\mathbf{k}} \exp \left( -\frac{1}{2} \left| \frac{v_{1\mathbf{k}}}{\omega_{\mathbf{k}}} - \frac{v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right|^2 \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right) \quad (608)$$

$$= U^{*1/2} S^{1/2}, \quad (609)$$

$$\left\langle \widetilde{B}_x(\tau) \widetilde{B}_x(0) \right\rangle_B = \frac{1}{4} \left\langle B_1^+ B_0^- (\tau) B_1^+ B_0^- + B_1^+ B_0^- (\tau) B_0^+ B_1^- - B_1^+ B_0^- (\tau) B_{10} - B_1^+ B_0^- (\tau) B_{01} + B_0^+ B_1^- (\tau) B_1^+ B_0^- \right. \quad (610)$$

$$\left. + B_0^+ B_1^- (\tau) B_0^+ B_1^- - B_0^+ B_1^- (\tau) B_{10} - B_0^+ B_1^- (\tau) B_{01} \right\rangle, \quad (611)$$

$$\left\langle \widetilde{B}_x(\tau) \widetilde{B}_x(0) \right\rangle_B = \frac{1}{4} \left\langle B_1^+ B_0^- (\tau) B_1^+ B_0^- + B_1^+ B_0^- (\tau) B_0^+ B_1^- - B_1^+ B_0^- (\tau) B_{10} - B_1^+ B_0^- (\tau) B_{01} \right. \quad (612)$$

$$\left. + B_0^+ B_1^- (\tau) B_1^+ B_0^- + B_0^+ B_1^- (\tau) B_0^+ B_1^- - B_0^+ B_1^- (\tau) B_{10} - B_0^+ B_1^- (\tau) B_{01} \right\rangle \quad (613)$$

$$= \frac{1}{4} \left( U^* \exp(-\phi(\tau)) S + \exp(\phi(\tau)) S - B_{10}^2 - |B_{10}|^2 + \exp(\phi(\tau)) S + U \exp(-\phi(\tau)) S - B_{10}^{*2} - |B_{10}|^2 \right) \quad (614)$$

$$= \frac{1}{4} \left( 2U^{\Re} \exp(-\phi(\tau)) S + 2 \exp(\phi(\tau)) S - 2(B_{10}^2)^{\Re} - 2|B_{10}|^2 \right) \quad (615)$$

$$= \frac{1}{4} \left( 2U^{\Re} \exp(-\phi(\tau)) S + 2 \exp(\phi(\tau)) S - 2(U^*)^{\Re} S - 2S \right) \quad (616)$$

$$= \frac{S}{2} \left( U^{\Re} \exp(-\phi(\tau)) + \exp(\phi(\tau)) - (U^*)^{\Re} - 1 \right), \quad (617)$$

$$\langle \widetilde{B}_y(\tau) \widetilde{B}_y(0) \rangle_B = \left\langle \frac{B_0^+ B_1^- (\tau) - B_1^+ B_0^- (\tau) + B_{10} - B_{01}}{2i} \frac{B_0^+ B_1^- - B_1^+ B_0^- + B_{10} - B_{01}}{2i} \right\rangle_B \quad (618)$$

$$= -\frac{1}{4} \langle (B_0^+ B_1^- (\tau) - B_1^+ B_0^- (\tau) + B_{10} - B_{01}) (B_0^+ B_1^- - B_1^+ B_0^- + B_{10} - B_{01}) \rangle_B \quad (619)$$

$$= -\frac{1}{4} \langle B_0^+ B_1^- (\tau) B_0^+ B_1^- - B_0^+ B_1^- (\tau) B_1^+ B_0^- + B_0^+ B_1^- (\tau) B_{10} - B_0^+ B_1^- (\tau) B_{01} - B_1^+ B_0^- (\tau) B_0^+ B_1^- + B_1^+ B_0^- (\tau) B_1^+ B_0^- \rangle \quad (620)$$

$$- B_1^+ B_0^- (\tau) B_{10} + B_1^+ B_0^- (\tau) B_{01} + B_{10} B_0^+ B_1^- - B_{10} B_1^+ B_0^- + B_{10} B_{01} - B_{01} B_0^+ B_1^- + B_{01} B_1^+ B_0^- - B_{01} B_{10} + B_{01} B_{01} \rangle \quad (621)$$

$$= -\frac{1}{4} \langle B_0^+ B_1^- (\tau) B_0^+ B_1^- - B_0^+ B_1^- (\tau) B_1^+ B_0^- + B_0^+ B_1^- (\tau) B_{10} - B_0^+ B_1^- (\tau) B_{01} \rangle \quad (622)$$

$$- B_1^+ B_0^- (\tau) B_0^+ B_1^- + B_1^+ B_0^- (\tau) B_1^+ B_0^- - B_1^+ B_0^- (\tau) B_{10} + B_1^+ B_0^- (\tau) B_{01} \rangle \quad (623)$$

$$= -\frac{1}{4} \langle B_0^+ B_1^- (\tau) B_0^+ B_1^- - B_0^+ B_1^- (\tau) B_1^+ B_0^- + B_{01} B_{10} - B_{01} B_{01} - B_1^+ B_0^- (\tau) B_0^+ B_1^- + B_1^+ B_0^- (\tau) B_1^+ B_0^- - B_{10} B_{10} + B_{10} B_{01} \rangle \quad (624)$$

$$= -\frac{1}{4} \left( U \exp(-\phi(\tau)) S - \exp(\phi(\tau)) S - \exp(\phi(\tau)) S + U^* \exp(-\phi(\tau)) S + 2S - 2(U^*)^{\Re} S \right) \quad (625)$$

$$= -\frac{S}{4} (2U^{\Re} \exp(-\phi(\tau)) - 2 \exp(\phi(\tau)) + 2 - 2U^{\Re}) \quad (626)$$

$$= \frac{S}{2} (\exp(\phi(\tau)) - U^{\Re} \exp(-\phi(\tau)) - 1 + U^{\Re}), \quad (627)$$

$$\langle \widetilde{B}_x(\tau) \widetilde{B}_y(0) \rangle_B = \left\langle \frac{B_1^+ B_0^- (\tau) + B_0^+ B_1^- (\tau) - B_{10} - B_{01}}{2} \frac{B_0^+ B_1^- - B_1^+ B_0^- + B_{10} - B_{01}}{2i} \right\rangle_B \quad (628)$$

$$= \frac{1}{4i} \langle (B_1^+ B_0^- (\tau) + B_0^+ B_1^- (\tau) - B_{10} - B_{01}) (B_0^+ B_1^- - B_1^+ B_0^- + B_{10} - B_{01}) \rangle_B \quad (629)$$

$$= \frac{1}{4i} \langle B_1^+ B_0^- (\tau) B_0^+ B_1^- - B_1^+ B_0^- (\tau) B_1^+ B_0^- + B_1^+ B_0^- (\tau) B_{10} - B_1^+ B_0^- (\tau) B_{01} + B_0^+ B_1^- (\tau) B_0^+ B_1^- - B_0^+ B_1^- (\tau) B_1^+ B_0^- + B_0^+ B_1^- (\tau) B_{10} \rangle \quad (630)$$

$$- B_0^+ B_1^- (\tau) B_{01} - B_{10} B_0^+ B_1^- + B_{10} B_1^+ B_0^- - B_{10} B_{10} + B_{10} B_{01} - B_{01} B_0^+ B_1^- + B_{01} B_1^+ B_0^- - B_{01} B_{10} + B_{01} B_{01} \rangle \quad (631)$$

$$= \frac{1}{4i} \langle B_1^+ B_0^- (\tau) B_0^+ B_1^- - B_1^+ B_0^- (\tau) B_1^+ B_0^- + B_1^+ B_0^- (\tau) B_{10} - B_1^+ B_0^- (\tau) B_{01} + B_0^+ B_1^- (\tau) B_0^+ B_1^- - B_0^+ B_1^- (\tau) B_1^+ B_0^- + B_0^+ B_1^- (\tau) B_{10} \rangle \quad (632)$$

$$- B_0^+ B_1^- (\tau) B_{01} \rangle \quad (633)$$

$$= \frac{1}{4i} \langle B_1^+ B_0^- (\tau) B_0^+ B_1^- - B_1^+ B_0^- (\tau) B_1^+ B_0^- + B_{10} B_{10} - B_{10} B_{01} + B_0^+ B_1^- (\tau) B_0^+ B_1^- - B_0^+ B_1^- (\tau) B_1^+ B_0^- + B_{01} B_{10} - B_{01} B_{01} \rangle \quad (634)$$

$$= \frac{1}{4i} \langle B_1^+ B_0^- (\tau) B_0^+ B_1^- - B_1^+ B_0^- (\tau) B_1^+ B_0^- + B_{10} B_{10} + B_0^+ B_1^- (\tau) B_0^+ B_1^- - B_0^+ B_1^- (\tau) B_1^+ B_0^- - B_{01} B_{01} \rangle \quad (635)$$

$$= \frac{1}{4i} (\exp(\phi(\tau)) S - U^* \exp(-\phi(\tau)) S + U \exp(-\phi(\tau)) S - \exp(\phi(\tau)) S + U^* S - US) \quad (636)$$

$$= \frac{1}{4i} (-U^* \exp(-\phi(\tau)) S + U \exp(-\phi(\tau)) S + U^* S - US) \quad (637)$$

$$= \frac{S}{4i} (-U^* \exp(-\phi(\tau)) + U \exp(-\phi(\tau)) + U^* - U) \quad (638)$$

$$= \frac{S(U - U^*)}{4i} (\exp(-\phi(\tau)) - 1) \quad (639)$$

$$= \frac{2iU^{\Im} S}{4i} (\exp(-\phi(\tau)) - 1) \quad (640)$$

$$= \frac{U^{\Im} S}{2} (\exp(-\phi(\tau)) - 1), \quad (641)$$

$$\langle \widetilde{B}_y(\tau) \widetilde{B}_x(0) \rangle_B = \left\langle \frac{B_0^+ B_1^- (\tau) - B_1^+ B_0^- (\tau) + B_{10} - B_{01}}{2i} \frac{B_1^+ B_0^- + B_0^+ B_1^- - B_{10} - B_{01}}{2} \right\rangle_B \quad (642)$$

$$= \frac{1}{4i} \langle (B_0^+ B_1^- (\tau) - B_1^+ B_0^- (\tau) + B_{10} - B_{01}) (B_1^+ B_0^- + B_0^+ B_1^- - B_{10} - B_{01}) \rangle_B \quad (643)$$

$$= \frac{1}{4i} \langle B_0^+ B_1^- (\tau) B_1^+ B_0^- + B_0^+ B_1^- (\tau) B_0^+ B_1^- - B_0^+ B_1^- (\tau) B_{10} - B_0^+ B_1^- (\tau) B_{01} - B_1^+ B_0^- (\tau) B_1^+ B_0^- - B_1^+ B_0^- (\tau) B_0^+ B_1^- \rangle \quad (644)$$

$$+ B_1^+ B_0^- (\tau) B_{10} + B_1^+ B_0^- (\tau) B_{01} + B_{10} B_1^+ B_0^- + B_{10} B_0^+ B_1^- - B_{10} B_{10} - B_{10} B_{01} - B_{01} B_1^+ B_0^- - B_{01} B_0^+ B_1^- + B_{01} B_{10} + B_{01} B_{01} \rangle \quad (645)$$

$$= \frac{1}{4i} \langle B_0^+ B_1^- (\tau) B_1^+ B_0^- + B_0^+ B_1^- (\tau) B_0^+ B_1^- - B_0^+ B_1^- (\tau) B_{10} - B_0^+ B_1^- (\tau) B_{01} \rangle \quad (646)$$

$$-B_1^+ B_0^- (\tau) B_1^+ B_0^- - B_1^+ B_0^- (\tau) B_0^+ B_1^- + B_1^+ B_0^- (\tau) B_{10} + B_1^+ B_0^- (\tau) B_{01} \rangle \quad (647)$$

$$= \frac{1}{4i} \langle B_0^+ B_1^- (\tau) B_1^+ B_0^- + B_0^+ B_1^- (\tau) B_0^+ B_1^- - B_{01} B_{10} - B_{01} B_{01} - B_1^+ B_0^- (\tau) B_1^+ B_0^- \rangle \quad (648)$$

$$-B_1^+ B_0^- (\tau) B_0^+ B_1^- + B_{10} B_{10} + B_{10} B_{01} \rangle \quad (649)$$

$$= \frac{1}{4i} \langle B_0^+ B_1^- (\tau) B_1^+ B_0^- + B_0^+ B_1^- (\tau) B_0^+ B_1^- - B_{01} B_{10} - B_{01} B_{01} - B_1^+ B_0^- (\tau) B_1^+ B_0^- \rangle \quad (650)$$

$$-B_1^+ B_0^- (\tau) B_0^+ B_1^- + B_{10} B_{10} + B_{10} B_{01} \rangle \quad (651)$$

$$= \frac{1}{4i} \langle B_0^+ B_1^-(\tau) B_1^+ B_0^- + B_0^+ B_1^-(\tau) B_0^+ B_1^- - B_{01} B_{01} - B_1^+ B_0^-(\tau) B_1^+ B_0^- - B_1^+ B_0^-(\tau) B_0^+ B_1^- + B_{10} B_{10} \rangle \quad (652)$$

$$= \frac{1}{4i} (U \exp(-\phi(\tau)) S - U^* \exp(-\phi(\tau)) S + B_{10}^2 - B_{10}^{*2}) \quad (653)$$

$$= \frac{1}{4i} (U \exp(-\phi(\tau)) S - U^* \exp(-\phi(\tau)) S + U^* S - U S) \quad (654)$$

$$= \frac{S(U - U^*)}{4i} (\exp(-\phi(\tau)) - 1) \quad (655)$$

$$= \frac{2iU^3 S}{4i} (\exp(-\phi(\tau)) - 1) \quad (656)$$

$$= -(g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right)^* (N_{\mathbf{k}'} + 1) B_{10}, \quad (657)$$

$$\langle B_1^\dagger B_0^-(\tau)(g_{i\mathbf{k}'}-v_{i\mathbf{k}'})^*b_{\mathbf{k}'}\rangle_B = (g_{i\mathbf{k}'}-v_{i\mathbf{k}'})^* \prod_{\mathbf{k}} \exp\left(\frac{1}{2}\left(\frac{v_{1\mathbf{k}}^*v_{0\mathbf{k}}-v_{1\mathbf{k}}v_{0\mathbf{k}}^*}{\omega_{\mathbf{k}}}\right)\right)\left(\frac{v_{1\mathbf{k}'}-v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}}e^{i\omega_{\mathbf{k}'}\tau}\right)N_{\mathbf{k}'}\langle\prod_{\mathbf{k}}\left(D\left(\frac{v_{1\mathbf{k}}-v_{0\mathbf{k}}}{\omega_{\mathbf{k}}}e^{i\omega_{\mathbf{k}}\tau}\right)\right)\rangle \quad (658)$$

$$= (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right) N_{\mathbf{k}'} B_{10}, \quad (659)$$

$$\langle B_0^\dagger B_1(\tau) (g_{i\mathbf{k}'} - v_{i\mathbf{k}'} b_{\mathbf{k}'}^\dagger) \rangle_B = -(g_{i\mathbf{k}'} - v_{i\mathbf{k}'} \left( \frac{v_0 \mathbf{k}' - v_1 \mathbf{k}'}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'} \tau} \right)^* (N_{\mathbf{k}'} + 1) B_{01}. \quad (660)$$

$$\langle B_0^+ B_1^-(\tau) (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* b_{\mathbf{k}'} \rangle_B = (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* \left( \frac{v_0 \mathbf{k}' - v_1 \mathbf{k}'}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'} \tau} \right) N_{\mathbf{k}'} B_{01}, \quad (661)$$

$$\langle \widetilde{B}_z(\tau) \widetilde{B}_z(0) \rangle_B = \frac{1}{2} \sum_{\mathbf{k}'} \left( -(g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) \left( \frac{v_{i\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right)^* (N_{\mathbf{k}'} + 1) B_{10} - (g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) \left( \frac{v_{0\mathbf{k}'} - v_{i\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right)^* (N_{\mathbf{k}'} + 1) B_{01} \right) \quad (662)$$

$$+(g_{i\mathbf{k}'}-v_{i\mathbf{k}'})^*\left(\frac{v_{1\mathbf{k}'}-v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}}e^{i\omega_{\mathbf{k}'}\tau}\right)N_{\mathbf{k}'}B_{10}+(g_{i\mathbf{k}'}-v_{i\mathbf{k}'})^*\left(\frac{v_{0\mathbf{k}'}-v_{1\mathbf{k}'}}{\omega_{\mathbf{k}'}}e^{i\omega_{\mathbf{k}'}\tau}\right)N_{\mathbf{k}'}B_{01}\quad (663)$$

$$= \frac{1}{2} \sum_{\mathbf{k}'} \left( -(g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right)^* (N_{\mathbf{k}'} + 1) B_{10} - (g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) \left( \frac{v_{0\mathbf{k}'} - v_{1\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right)^* (N_{\mathbf{k}'} + 1) B_{01} \right) \quad (664)$$

$$+(g_{i\mathbf{k}'}-v_{i\mathbf{k}'})^*\left(\frac{v_{1\mathbf{k}'}-v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}}e^{i\omega_{\mathbf{k}'}\tau}\right)N_{\mathbf{k}'}B_{10}+(g_{i\mathbf{k}'}-v_{i\mathbf{k}'})^*\left(\frac{v_{0\mathbf{k}'}-v_{1\mathbf{k}'}}{\omega_{\mathbf{k}'}}e^{i\omega_{\mathbf{k}'}\tau}\right)N_{\mathbf{k}'}B_{01}\quad (665)$$

$$= \frac{1}{2} \sum_{\mathbf{k}'} \left( - (g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) (N_{\mathbf{k}'} + 1) \left( \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right)^* B_{10} + \left( \frac{v_{0\mathbf{k}'} - v_{1\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right)^* B_{01} \right) \right) \quad (666)$$

$$+ (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* N_{\mathbf{k}'} \left( \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right) B_{10} + \left( \frac{v_{0\mathbf{k}'} - v_{1\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right) B_{01} \right) \quad (667)$$

$$= \frac{1}{2} \sum_{\mathbf{k}'} \left( - (g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) (N_{\mathbf{k}'} + 1) \left( \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right)^* B_{10} - \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right)^* B_{01} \right) \right) \quad (668)$$

$$+ (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* N_{\mathbf{k}'} \left( \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right) B_{10} - \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right) B_{01} \right) \quad (669)$$

$$= \frac{1}{2} \sum_{\mathbf{k}'} \left( -(g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) (N_{\mathbf{k}'} + 1) \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'} \tau} \right)^* (B_{10} - B_{01}) + (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* N_{\mathbf{k}'} \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'} \tau} \right) (B_{10} - B_{01}) \right) \quad (670)$$

$$= \frac{1}{2} \sum_{\mathbf{k}'} 2iB_{10}^{\mathfrak{S}} \left( (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* N_{\mathbf{k}'} \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right) - (g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) (N_{\mathbf{k}'} + 1) \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right)^* \right) \quad (671)$$

$$= i \sum_{\mathbf{k}'} B_{10}^{\mathfrak{Z}} \left( (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* N_{\mathbf{k}'} \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right) - (g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) (N_{\mathbf{k}'} + 1) \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} e^{i\omega_{\mathbf{k}'}\tau} \right)^* \right) \quad (672)$$

$$= i \sum_{\mathbf{k}'} B_{10}^{\mathfrak{S}} \left( (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* N_{\mathbf{k}'} \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right) e^{i\omega_{\mathbf{k}'}\tau} - (g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) (N_{\mathbf{k}'} + 1) \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right)^* e^{-i\omega_{\mathbf{k}'}\tau} \right), \quad (673)$$







$$+e^{-i\omega_{\mathbf{k}'}\tau} (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* \left( \left( \frac{v_{0\mathbf{k}'} - v_{1\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right) (N_{\mathbf{k}'} + 1) B_{10}^* \right) - e^{-i\omega_{\mathbf{k}'}\tau} (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* \left( \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right) (N_{\mathbf{k}'} + 1) B_{10} \right) \right) \quad (732)$$

$$= \frac{1}{2i} \sum_{\mathbf{k}'} \left( e^{i\omega_{\mathbf{k}'}\tau} \left( - (g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) \left( \frac{v_{0\mathbf{k}'} - v_{1\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right)^* B_{10}^* N_{\mathbf{k}'} + (g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right)^* B_{10} N_{\mathbf{k}'} \right) \right) \quad (733)$$

$$+ e^{-i\omega_{\mathbf{k}'}\tau} \left( (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* \left( \left( \frac{v_{0\mathbf{k}'} - v_{1\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right) (N_{\mathbf{k}'} + 1) B_{10}^* \right) - (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* \left( \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right) (N_{\mathbf{k}'} + 1) B_{10} \right) \right) \quad (734)$$

$$= \frac{1}{2i} \sum_{\mathbf{k}'} \left( e^{i\omega_{\mathbf{k}'}\tau} (g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right)^* (B_{10} + B_{10}^*) N_{\mathbf{k}'} \right) \quad (735)$$

$$- e^{-i\omega_{\mathbf{k}'}\tau} (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right) (B_{10} + B_{10}^*) (N_{\mathbf{k}'} + 1) \right) \quad (736)$$

$$= \frac{1}{i} \sum_{\mathbf{k}'} \left( e^{i\omega_{\mathbf{k}'}\tau} (g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right)^* B_{10}^{\Re} N_{\mathbf{k}'} - e^{-i\omega_{\mathbf{k}'}\tau} (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right) B_{10}^{\Re} (N_{\mathbf{k}'} + 1) \right) \quad (737)$$

$$= i \sum_{\mathbf{k}'} \left( e^{-i\omega_{\mathbf{k}'}\tau} (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right) B_{10}^{\Re} (N_{\mathbf{k}'} + 1) - e^{i\omega_{\mathbf{k}'}\tau} (g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right)^* B_{10}^{\Re} N_{\mathbf{k}'} \right) \quad (738)$$

$$= i \sum_{\mathbf{k}'} \left( e^{-i\omega_{\mathbf{k}'}\tau} (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right) B_{10}^{\Re} (N_{\mathbf{k}'} + 1) - e^{i\omega_{\mathbf{k}'}\tau} (g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right)^* B_{10}^{\Re} N_{\mathbf{k}'} \right) \quad (739)$$

$$= i B_{10}^{\Re} \sum_{\mathbf{k}'} \left( e^{-i\omega_{\mathbf{k}'}\tau} (g_{i\mathbf{k}'} - v_{i\mathbf{k}'})^* \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right) (N_{\mathbf{k}'} + 1) - e^{i\omega_{\mathbf{k}'}\tau} (g_{i\mathbf{k}'} - v_{i\mathbf{k}'}) \left( \frac{v_{1\mathbf{k}'} - v_{0\mathbf{k}'}}{\omega_{\mathbf{k}'}} \right)^* N_{\mathbf{k}'} \right) \quad (740)$$

The correlation functions are equal to:

$$\langle \widetilde{B_{iz}}(\tau) \widetilde{B_{jz}}(0) \rangle_B = \sum_{\mathbf{k}} ((g_{i\mathbf{k}} - v_{i\mathbf{k}}) (g_{j\mathbf{k}} - v_{j\mathbf{k}})^* e^{i\omega_{\mathbf{k}}\tau} N_{\mathbf{k}} + (g_{i\mathbf{k}} - v_{i\mathbf{k}})^* (g_{j\mathbf{k}} - v_{j\mathbf{k}}) e^{-i\omega_{\mathbf{k}}\tau} (N_{\mathbf{k}} + 1)), \quad (741)$$

$$U = \prod_{\mathbf{k}} \left( \exp \left( \frac{v_{0\mathbf{k}}^* v_{1\mathbf{k}} - v_{0\mathbf{k}} v_{1\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right) \right), \quad (742)$$

$$\phi(\tau) = \sum_{\mathbf{k}} \left| \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right|^2 \left( -i \sin(\omega_{\mathbf{k}}\tau) + \cos(\omega_{\mathbf{k}}\tau) \coth \left( \frac{\beta \omega_{\mathbf{k}}}{2} \right) \right), \quad (743)$$

$$\langle \widetilde{B_x}(\tau) \widetilde{B_x}(0) \rangle_B = \frac{|B_{10}|^2}{2} (U^{\Re} \exp(-\phi(\tau)) + \exp(\phi(\tau)) - U^{\Re} - 1), \quad (744)$$

$$\langle \widetilde{B_y}(\tau) \widetilde{B_y}(0) \rangle_B = \frac{|B_{10}|^2}{2} (\exp(\phi(\tau)) - U^{\Re} \exp(-\phi(\tau)) - 1 + U^{\Re}), \quad (745)$$

$$\langle \widetilde{B_x}(\tau) \widetilde{B_y}(0) \rangle_B = \frac{U^{\Im} |B_{10}|^2}{2} (\exp(-\phi(\tau)) - 1), \quad (746)$$

$$\langle \widetilde{B_y}(\tau) \widetilde{B_x}(0) \rangle_B = \frac{U^{\Im} |B_{10}|^2}{2} (\exp(-\phi(\tau)) - 1), \quad (747)$$

$$\langle \widetilde{B_{iz}}(\tau) \widetilde{B_x}(0) \rangle_B = i B_{10}^{\Im} \sum_{\mathbf{k}} \left( (g_{i\mathbf{k}} - v_{i\mathbf{k}}) N_{\mathbf{k}} e^{i\omega_{\mathbf{k}}\tau} \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right)^* - (g_{i\mathbf{k}} - v_{i\mathbf{k}})^* \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} e^{-i\omega_{\mathbf{k}}\tau} (N_{\mathbf{k}} + 1) \right), \quad (748)$$

$$\langle \widetilde{B_x}(\tau) \widetilde{B_{iz}}(0) \rangle_B = i B_{10}^{\Im} \sum_{\mathbf{k}} \left( (g_{i\mathbf{k}} - v_{i\mathbf{k}})^* N_{\mathbf{k}} e^{i\omega_{\mathbf{k}}\tau} \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right) - (g_{i\mathbf{k}} - v_{i\mathbf{k}}) \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right)^* e^{-i\omega_{\mathbf{k}}\tau} (N_{\mathbf{k}} + 1) \right), \quad (749)$$

$$\langle \widetilde{B_{iz}}(\tau) \widetilde{B_y}(0) \rangle_B = i B_{10}^{\Re} \sum_{\mathbf{k}} \left( e^{-i\omega_{\mathbf{k}}\tau} (g_{i\mathbf{k}} - v_{i\mathbf{k}})^* \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right) (N_{\mathbf{k}} + 1) - e^{i\omega_{\mathbf{k}}\tau} (g_{i\mathbf{k}} - v_{i\mathbf{k}}) \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right)^* N_{\mathbf{k}} \right), \quad (750)$$

$$\langle \widetilde{B_y}(\tau) \widetilde{B_{iz}}(0) \rangle_B = i B_{10}^{\Re} \sum_{\mathbf{k}} \left( (g_{i\mathbf{k}} - v_{i\mathbf{k}})^* N_{\mathbf{k}} e^{i\omega_{\mathbf{k}}\tau} \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right) - (g_{i\mathbf{k}} - v_{i\mathbf{k}}) (N_{\mathbf{k}} + 1) e^{-i\omega_{\mathbf{k}}\tau} \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right)^* \right). \quad (751)$$

The spectral density is defined in the usual way:

$$J_i(\omega) \equiv \sum_{\mathbf{k}} |g_{i\mathbf{k}}|^2 \delta(\omega - \omega_{\mathbf{k}}), \quad (752)$$

$$v_{i\mathbf{k}} = g_{i\mathbf{k}} F_i(\omega_{\mathbf{k}}). \quad (753)$$

it takes account of the density of states, dispersion relation and interaction mechanism with the environment. In the continuous case a way to measure the strenght of the system-environment coupling is:

$$\lambda_i = \int_0^\infty \frac{J_i(\omega)}{\omega} d\omega. \quad (754)$$

The integral version of the correlation functions are given by:

$$\langle \widetilde{B_{iz}(\tau)} \widetilde{B_{jz}(0)} \rangle_B = \sum_{\mathbf{k}} ((g_{i\mathbf{k}} - v_{i\mathbf{k}})(g_{j\mathbf{k}} - v_{j\mathbf{k}})^* e^{i\omega_{\mathbf{k}}\tau} N_{\mathbf{k}} + (g_{i\mathbf{k}} - v_{i\mathbf{k}})^*(g_{j\mathbf{k}} - v_{j\mathbf{k}}) e^{-i\omega_{\mathbf{k}}\tau} (N_{\mathbf{k}} + 1)) \quad (755)$$

$$= \sum_{\mathbf{k}} ((g_{i\mathbf{k}} - g_{i\mathbf{k}} F_i(\omega_{\mathbf{k}}))(g_{j\mathbf{k}} - g_{j\mathbf{k}} F_j(\omega_{\mathbf{k}}))^* e^{i\omega_{\mathbf{k}}\tau} N_{\mathbf{k}} + (g_{i\mathbf{k}} - g_{i\mathbf{k}} F_i(\omega_{\mathbf{k}}))^*(g_{j\mathbf{k}} - g_{j\mathbf{k}} F_j(\omega_{\mathbf{k}})) e^{-i\omega_{\mathbf{k}}\tau} (N_{\mathbf{k}} + 1)) \quad (756)$$

$$= \sum_{\mathbf{k}} (g_{i\mathbf{k}}(1 - F_i(\omega_{\mathbf{k}})) g_{j\mathbf{k}}^*(1 - F_j(\omega_{\mathbf{k}}))^* e^{i\omega_{\mathbf{k}}\tau} N_{\mathbf{k}} + g_{i\mathbf{k}}^*(1 - F_i(\omega_{\mathbf{k}}))^* g_{j\mathbf{k}}(1 - F_j(\omega_{\mathbf{k}})) e^{-i\omega_{\mathbf{k}}\tau} (N_{\mathbf{k}} + 1)) \quad (757)$$

$$\approx \int_0^\infty (\sqrt{J_i(\omega) J_j^*(\omega)} (1 - F_i(\omega)) (1 - F_j^*(\omega)) e^{i\omega\tau} N(\omega) + \sqrt{J_i^*(\omega) J_j(\omega)} (1 - F_i^*(\omega)) (1 - F_j(\omega)) e^{-i\omega\tau} (N(\omega) + 1)) d\omega, \quad (758)$$

$$U = \prod_{\mathbf{k}} \left( \exp \left( \frac{v_{0\mathbf{k}}^* v_{1\mathbf{k}} - v_{0\mathbf{k}} v_{1\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right) \right) \quad (759)$$

$$= \exp \left( \sum_{\mathbf{k}} \frac{v_{0\mathbf{k}}^* v_{1\mathbf{k}} - v_{0\mathbf{k}} v_{1\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right) \quad (760)$$

$$= \exp \left( \sum_{\mathbf{k}} \frac{g_{0\mathbf{k}}^* F_0^*(\omega_{\mathbf{k}}) g_{1\mathbf{k}} F_1(\omega_{\mathbf{k}}) - g_{0\mathbf{k}} F_0(\omega_{\mathbf{k}}) g_{1\mathbf{k}}^* F_1^*(\omega_{\mathbf{k}})}{\omega_{\mathbf{k}}^2} \right) \quad (761)$$

$$= \exp \left( \sum_{\mathbf{k}} \frac{g_{0\mathbf{k}}^* F_0^*(\omega_{\mathbf{k}}) g_{1\mathbf{k}} F_1(\omega_{\mathbf{k}}) - g_{0\mathbf{k}} F_0(\omega_{\mathbf{k}}) g_{1\mathbf{k}}^* F_1^*(\omega_{\mathbf{k}})}{\omega_{\mathbf{k}}^2} \right) \quad (762)$$

$$= \exp \left( \sum_{\mathbf{k}} \frac{g_{0\mathbf{k}}^* g_{1\mathbf{k}} F_0^*(\omega_{\mathbf{k}}) F_1(\omega_{\mathbf{k}}) - g_{0\mathbf{k}} g_{1\mathbf{k}}^* F_0(\omega_{\mathbf{k}}) F_1^*(\omega_{\mathbf{k}})}{\omega_{\mathbf{k}}^2} \right) \quad (763)$$

$$\approx \exp \left( \int_0^\infty \frac{\sqrt{J_0^*(\omega) J_1(\omega)} F_0^*(\omega) F_1(\omega) - \sqrt{J_0(\omega) J_1^*(\omega)} F_0(\omega) F_1^*(\omega)}{\omega^2} d\omega \right), \quad (764)$$

$$\phi(\tau) = \sum_{\mathbf{k}} \left| \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right|^2 \left( -i \sin(\omega_{\mathbf{k}}\tau) + \cos(\omega_{\mathbf{k}}\tau) \coth \left( \frac{\beta\omega_{\mathbf{k}}}{2} \right) \right) \quad (765)$$

$$= \sum_{\mathbf{k}} \left| \frac{g_{1\mathbf{k}} F_1(\omega_{\mathbf{k}}) - g_{0\mathbf{k}} F_0(\omega_{\mathbf{k}})}{\omega_{\mathbf{k}}} \right|^2 \left( -i \sin(\omega_{\mathbf{k}}\tau) + \cos(\omega_{\mathbf{k}}\tau) \coth \left( \frac{\beta\omega_{\mathbf{k}}}{2} \right) \right) \quad (766)$$

$$\approx \int_0^\infty \left| \frac{\sqrt{J_1(\omega)} F_1(\omega) - \sqrt{J_0(\omega)} F_0(\omega)}{\omega} \right|^2 \left( -i \sin(\omega\tau) + \cos(\omega\tau) \coth \left( \frac{\beta\omega}{2} \right) \right) d\omega, \quad (767)$$

$$B_{10} = \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \left| \frac{v_{1\mathbf{k}}}{\omega_{\mathbf{k}}} - \frac{v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right|^2 \coth \left( \frac{\beta\omega_{\mathbf{k}}}{2} \right) \right) \exp \left( \sum_{\mathbf{k}} \frac{1}{2} \left( \frac{v_{1\mathbf{k}}^* v_{0\mathbf{k}} - v_{1\mathbf{k}} v_{0\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right) \right) \quad (768)$$

$$= \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \left| \frac{g_{1\mathbf{k}} F_1(\omega_{\mathbf{k}})}{\omega_{\mathbf{k}}} - \frac{g_{0\mathbf{k}} F_0(\omega_{\mathbf{k}})}{\omega_{\mathbf{k}}} \right|^2 \coth \left( \frac{\beta\omega_{\mathbf{k}}}{2} \right) \right) \exp \left( \sum_{\mathbf{k}} \frac{1}{2} \left( \frac{v_{1\mathbf{k}}^* v_{0\mathbf{k}} - v_{1\mathbf{k}} v_{0\mathbf{k}}^*}{\omega_{\mathbf{k}}^2} \right) \right) \quad (769)$$

$$= \exp\left(-\frac{1}{2} \sum_{\mathbf{k}} \left| \frac{g_{1\mathbf{k}} F_1(\omega_{\mathbf{k}})}{\omega_{\mathbf{k}}} - \frac{g_{0\mathbf{k}} F_0(\omega_{\mathbf{k}})}{\omega_{\mathbf{k}}} \right|^2 \coth\left(\frac{\beta \omega_{\mathbf{k}}}{2}\right)\right) \exp\left(\sum_{\mathbf{k}} \frac{1}{2} \left( \frac{g_{0\mathbf{k}} F_0(\omega_{\mathbf{k}}) g_{1\mathbf{k}}^* F_1^*(\omega_{\mathbf{k}}) - g_{1\mathbf{k}} F_1(\omega_{\mathbf{k}}) g_{0\mathbf{k}}^* F_0^*(\omega_{\mathbf{k}})}{\omega_{\mathbf{k}}^2} \right)\right) \quad (770)$$

$$\approx \exp\left(-\frac{1}{2} \int_0^\infty \left| \frac{\sqrt{J_1(\omega)} F_1(\omega) - \sqrt{J_0(\omega)} F_0(\omega)}{\omega} \right|^2 \coth\left(\frac{\beta \omega}{2}\right) d\omega\right) \exp\left(\int_0^\infty \frac{1}{2} \left( \frac{\sqrt{J_0(\omega)} J_1^*(\omega) F_0(\omega) F_1^*(\omega) - \sqrt{J_1(\omega)} J_0^*(\omega) F_0^*(\omega) F_1(\omega)}{\omega^2} \right) d\omega\right), \quad (771)$$

$$\langle \widetilde{B}_x(\tau) \widetilde{B}_x(0) \rangle_B = \frac{|B_{10}|^2}{2} (U^{\Re} \exp(-\phi(\tau)) + \exp(\phi(\tau)) - U^{\Re} - 1), \quad (772)$$

$$\langle \widetilde{B}_y(\tau) \widetilde{B}_y(0) \rangle_B = \frac{|B_{10}|^2}{2} (\exp(\phi(\tau)) - U^{\Re} \exp(-\phi(\tau)) - 1 + U^{\Re}), \quad (773)$$

$$\langle \widetilde{B}_x(\tau) \widetilde{B}_y(0) \rangle_B = \frac{U^{\Im} |B_{10}|^2}{2} (\exp(-\phi(\tau)) - 1), \quad (774)$$

$$\langle \widetilde{B}_y(\tau) \widetilde{B}_x(0) \rangle_B = \frac{U^{\Im} |B_{10}|^2}{2} (\exp(-\phi(\tau)) - 1), \quad (775)$$

$$\langle \widetilde{B}_{iz}(\tau) \widetilde{B}_x(0) \rangle_B = i B_{10}^{\Im} \sum_{\mathbf{k}} \left( (g_{i\mathbf{k}} - v_{i\mathbf{k}}) N_{\mathbf{k}} e^{i\omega_{\mathbf{k}} \tau} \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right)^* - (g_{i\mathbf{k}} - v_{i\mathbf{k}})^* \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} e^{-i\omega_{\mathbf{k}} \tau} (N_{\mathbf{k}} + 1) \right) \quad (776)$$

$$= i B_{10}^{\Im} \sum_{\mathbf{k}} \left( (g_{i\mathbf{k}} - g_{i\mathbf{k}} F_i(\omega_{\mathbf{k}})) N_{\mathbf{k}} e^{i\omega_{\mathbf{k}} \tau} \left( \frac{g_{1\mathbf{k}} F_1(\omega_{\mathbf{k}}) - g_{0\mathbf{k}} F_0(\omega_{\mathbf{k}})}{\omega_{\mathbf{k}}} \right)^* - (g_{i\mathbf{k}} - g_{i\mathbf{k}} F_i(\omega_{\mathbf{k}}))^* \frac{g_{1\mathbf{k}} F_1(\omega_{\mathbf{k}}) - g_{0\mathbf{k}} F_0(\omega_{\mathbf{k}})}{\omega_{\mathbf{k}}} e^{-i\omega_{\mathbf{k}} \tau} (N_{\mathbf{k}} + 1) \right) \quad (777)$$

$$= i B_{10}^{\Im} \sum_{\mathbf{k}} \left( g_{i\mathbf{k}} (1 - F_i(\omega_{\mathbf{k}})) N_{\mathbf{k}} e^{i\omega_{\mathbf{k}} \tau} \left( \frac{g_{1\mathbf{k}} F_1(\omega_{\mathbf{k}}) - g_{0\mathbf{k}} F_0(\omega_{\mathbf{k}})}{\omega_{\mathbf{k}}} \right)^* - g_{i\mathbf{k}}^* (1 - F_i(\omega_{\mathbf{k}}))^* \frac{g_{1\mathbf{k}} F_1(\omega_{\mathbf{k}}) - g_{0\mathbf{k}} F_0(\omega_{\mathbf{k}})}{\omega_{\mathbf{k}}} e^{-i\omega_{\mathbf{k}} \tau} (N_{\mathbf{k}} + 1) \right), \quad (778)$$

$$Q(\omega) = \sqrt{J_i(\omega)} (1 - F_i(\omega)) \left( \frac{\sqrt{J_1(\omega)} F_1(\omega) - \sqrt{J_0(\omega)} F_0(\omega)}{\omega} \right)^*, \quad (779)$$

$$\langle \widetilde{B}_{iz}(\tau) \widetilde{B}_x(0) \rangle_B \approx i B_{10}^{\Im} \int_0^\infty (Q(\omega) N(\omega) e^{i\omega \tau} - Q^*(\omega) (N(\omega) + 1) e^{-i\omega \tau}) d\omega, \quad (780)$$

$$\langle \widetilde{B}_x(\tau) \widetilde{B}_{iz}(0) \rangle_B = i B_{10}^{\Im} \sum_{\mathbf{k}} \left( (g_{i\mathbf{k}} - v_{i\mathbf{k}})^* N_{\mathbf{k}} e^{i\omega_{\mathbf{k}} \tau} \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right) - (g_{i\mathbf{k}} - v_{i\mathbf{k}}) \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right)^* e^{-i\omega_{\mathbf{k}} \tau} (N_{\mathbf{k}} + 1) \right) \quad (781)$$

$$= i B_{10}^{\Im} \sum_{\mathbf{k}} \left( g_{i\mathbf{k}}^* (1 - F_i^*(\omega_{\mathbf{k}})) \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} N_{\mathbf{k}} e^{i\omega_{\mathbf{k}} \tau} - g_{i\mathbf{k}} (1 - F_i(\omega_{\mathbf{k}})) \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right)^* e^{-i\omega_{\mathbf{k}} \tau} (N_{\mathbf{k}} + 1) \right) \quad (782)$$

$$\approx i B_{10}^{\Im} \int_0^\infty (Q^*(\omega) N(\omega) e^{i\omega \tau} - Q(\omega) (N(\omega) + 1) e^{-i\omega \tau}) d\omega, \quad (783)$$

$$\langle \widetilde{B}_{iz}(\tau) \widetilde{B}_y(0) \rangle_B = i B_{10}^{\Re} \sum_{\mathbf{k}} \left( e^{-i\omega_{\mathbf{k}} \tau} (g_{i\mathbf{k}} - v_{i\mathbf{k}})^* \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right) (N_{\mathbf{k}} + 1) - e^{i\omega_{\mathbf{k}} \tau} (g_{i\mathbf{k}} - v_{i\mathbf{k}}) \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right)^* N_{\mathbf{k}} \right) \quad (784)$$

$$= i B_{10}^{\Re} \sum_{\mathbf{k}} \left( e^{-i\omega_{\mathbf{k}} \tau} g_{i\mathbf{k}}^* (1 - F_i^*(\omega_{\mathbf{k}})) \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right) (N_{\mathbf{k}} + 1) - e^{i\omega_{\mathbf{k}} \tau} g_{i\mathbf{k}} (1 - F_i(\omega_{\mathbf{k}})) \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right)^* N_{\mathbf{k}} \right) \quad (785)$$

$$\approx i B_{10}^{\Re} \int_0^\infty (e^{-i\omega \tau} Q^*(\omega) (N(\omega) + 1) - e^{i\omega \tau} Q(\omega) N(\omega)) d\omega, \quad (786)$$

$$\langle \widetilde{B}_y(\tau) \widetilde{B}_{iz}(0) \rangle_B = i B_{10}^{\Re} \sum_{\mathbf{k}} \left( (g_{i\mathbf{k}} - v_{i\mathbf{k}})^* N_{\mathbf{k}} e^{i\omega_{\mathbf{k}} \tau} \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right) - (g_{i\mathbf{k}} - v_{i\mathbf{k}}) (N_{\mathbf{k}} + 1) e^{-i\omega_{\mathbf{k}} \tau} \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right)^* \right) \quad (787)$$

$$= i B_{10}^{\Re} \sum_{\mathbf{k}} \left( g_{i\mathbf{k}}^* (1 - F_i^*(\omega_{\mathbf{k}})) N_{\mathbf{k}} e^{i\omega_{\mathbf{k}} \tau} \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right) - g_{i\mathbf{k}} (1 - F_i(\omega_{\mathbf{k}})) (N_{\mathbf{k}} + 1) e^{-i\omega_{\mathbf{k}} \tau} \left( \frac{v_{1\mathbf{k}} - v_{0\mathbf{k}}}{\omega_{\mathbf{k}}} \right)^* \right) \quad (788)$$

$$= i B_{10}^{\Re} \int_0^\infty (e^{i\omega \tau} Q^*(\omega) N(\omega) - e^{-i\omega \tau} Q(\omega) (N(\omega) + 1)) d\omega. \quad (789)$$

The eigenvalues of the Hamiltonian  $\overline{H_S}$  are given by the solution of the following algebraic equation:

$$\lambda^2 - \text{Tr}(\overline{H_S}) \lambda + \text{Det}(\overline{H_S}) = 0. \quad (790)$$

The solutions of this equation written in terms of  $\eta$  and  $\xi$  as defined in the previous section are given by  $\lambda_{\pm} = \frac{\xi \pm \eta}{2}$  and they satisfy  $H_S |\pm\rangle = \lambda_{\pm} |\pm\rangle$ . Using this notation is possible to write  $H_S = \lambda_+ |+\rangle\langle+| + \lambda_- |-\rangle\langle-|$ .

The time-dependence of the system operators  $\widetilde{A}_i(t)$  may be made explicit using the Fourier decomposition, in the case for time-independent  $\overline{H_S}$  we will obtain:

$$\widetilde{A}_i(\tau) = e^{i\overline{H}_S\tau} A_i e^{-i\overline{H}_S\tau} \quad (791)$$

$$= \sum_w e^{-iw\tau} \mathcal{A}_i(w). \quad (792)$$

Where the sum is defined on the set of all the differences between the eigenvalues of the system, in our case  $w \in \{0, \pm\eta\}$ .

In order to use the equation (792) to descompose the equation (355) we need to consider the time ordering operator  $\mathcal{T}$ , it's possible to write using the Dyson series or the expansion of the operator of the form  $U(t) \equiv \mathcal{T} \exp\left(-i \int_0^t dt' \overline{H}_S(t')\right)$  like:

$$U(t) \equiv \mathcal{T} \exp\left(-i \int_0^t dt' \overline{H}_S(t')\right) \quad (793)$$

$$= \mathbb{I} + \sum_{n=1}^{\infty} (-i)^n \int_0^t dt_1 \int_0^{t_1} dt_2 \dots \int_0^{t_{n-1}} dt_n H(t_1) H(t_2) \dots H(t_n). \quad (794)$$

Here  $0 < t_1 < t_2 < \dots < t_{n-1} < t_n = t$  is a partition of the set  $[0, t]$ . We will use a perturbative solution to the exponential of a time-varying operator, this can be done if we write an effective hamiltonian  $H_E(t)$  such that  $\mathcal{T} \exp\left(-i \int_0^t dt' \overline{H}_S(t')\right) \equiv \exp(-it H_E(t))$ . The effective Hamiltonian is expanded in a series of terms of increasing order in time  $H_E(t) = H_E^{(0)}(t) + H_E^{(1)}(t) + H_E^{(2)}(t) + \dots$  so we can write:

$$U(t) = \exp\left(-it \left(H_E^{(0)}(t) + H_E^{(1)}(t) + H_E^{(2)}(t) + \dots\right)\right). \quad (795)$$

The terms can be found expanding  $\mathcal{T} \exp\left(-i \int_0^t dt' \overline{H}_S(t')\right)$  and  $U(t)$  then equating the terms of the same power. The lowest terms are:

$$H_E^{(0)}(t) = \frac{1}{t} \int_0^t \overline{H}_S(t') dt', \quad (796)$$

$$H_E^{(1)}(t) = -\frac{i}{2t} \int_0^t dt' \int_0^{t'} dt'' [\overline{H}_S(t'), \overline{H}_S(t'')], \quad (797)$$

$$H_E^{(2)}(t) = \frac{1}{6t} \int_0^t dt' \int_0^{t'} dt'' \int_0^{t''} dt''' ([\overline{H}_S(t'), \overline{H}_S(t'')], \overline{H}_S(t''')) + [[\overline{H}_S(t'''), \overline{H}_S(t'')], \overline{H}_S(t')]. \quad (798)$$

In this case the Fourier decomposition using the Magnus expansion is

$$\widetilde{A}_i(t) = U^\dagger(t) A_i(t) U(t) \quad (799)$$

$$= e^{iH_E(t)t} A_i(t) e^{-iH_E(t)t} \quad (800)$$

$$= \sum_{w(t)} e^{-iw(t)t} \mathcal{A}_i(w(t)). \quad (801)$$

$w(t)$  belongs to the set of differences of eigenvalues of  $H_E(t)$  that depends of the time. As we can see the decomposition matrices are time-dependent as well.

Extending the Fourier decomposition to the matrix  $\widetilde{A}_j(t - \tau, t)$  using the Magnus expansion generates:

$$\widetilde{A}_j(t-\tau, t) = U(t) U^\dagger(t-\tau) A_j(t) U(t-\tau) U^\dagger(t) \quad (802)$$

$$= e^{-itH_E(t)} e^{i(t-\tau)H_E(t-\tau)} A_j(t) e^{-i(t-\tau)H_E(t-\tau)} e^{itH_E(t)} \quad (803)$$

$$= e^{-itH_E(t)} \left( \sum_{w'(t-\tau)} e^{-i(t-\tau)w(t-\tau)} \mathcal{A}_j(w(t-\tau)) \right) e^{itH_E(t)} \quad (804)$$

$$= \sum_{w(t), w'(t-\tau)} e^{iw'(t)t} e^{-i(t-\tau)w(t-\tau)} \mathcal{A}_j(w(t-\tau), w'(t)) \quad (805)$$

$$= \sum_{w(t), w'(t-\tau)} e^{iw'(t)t} e^{-i(t-\tau)w(t-\tau)} \mathcal{A}_j(w(t-\tau), w'(t)) \quad (806)$$

$$= \sum_{w(t), w'(t-\tau)} e^{i\tau w(t-\tau)} e^{-it(w(t-\tau)-w'(t))} \mathcal{A}_j(w(t-\tau), w'(t)) \quad (807)$$

where  $w'(t-\tau)$  and  $w(t)$  belongs to the set of the differences of the eigenvalues of the Hamiltonian  $\overline{H_E}(t-\tau)$  and  $\overline{H_E}(t)$  respectively.

In order to show the explicit form of the matrices present in the RHS of the equation (792) for a general  $2 \times 2$  matrix in a given time let's write the matrix  $A_i$  in the base  $V = \{|+\rangle, |-\rangle\}$  in the following way:

$$A_i = \sum_{\alpha, \beta \in V} \langle \alpha | A_i | \beta \rangle | \alpha \rangle \langle \beta |. \quad (808)$$

Given that  $[|+\rangle\langle+|, |-\rangle\langle-|] = 0$ , then using the Zassenhaus formula we obtain:

$$e^{i\overline{H_E}\tau} = e^{i(\lambda_+|+\rangle\langle+| + \lambda_-|-\rangle\langle-|)\tau} \quad (809)$$

$$= e^{i\lambda_+|+\rangle\langle+|\tau} e^{i\lambda_-|-\rangle\langle-|\tau} \quad (810)$$

$$= (|-\rangle\langle-| + e^{i\lambda_+\tau}|+\rangle\langle+|) (|+\rangle\langle+| + e^{i\lambda_-\tau}|-\rangle\langle-|) \quad (811)$$

$$= e^{i\lambda_+\tau}|+\rangle\langle+| + e^{i\lambda_-\tau}|-\rangle\langle-|. \quad (812)$$

Calculating the transformation (792) directly using the previous relationship we find that:

$$U^\dagger(\tau) A_i(\tau) U(\tau) = (e^{i\lambda_+\tau}|+\rangle\langle+| + e^{i\lambda_-\tau}|-\rangle\langle-|) \left( \sum_{\alpha, \beta \in V} \langle \alpha | A_i(\tau) | \beta \rangle | \alpha \rangle \langle \beta | \right) (e^{-i\lambda_+\tau}|+\rangle\langle+| + e^{-i\lambda_-\tau}|-\rangle\langle-|) \quad (813)$$

$$= \langle + | A_i(\tau) | + \rangle | + \rangle \langle + | + e^{i\eta\tau} \langle + | A_i(\tau) | - \rangle | + \rangle \langle - | + e^{-i\eta\tau} \langle - | A_i(\tau) | + \rangle | - \rangle \langle + | + \langle - | A_i(\tau) | - \rangle | - \rangle \langle - |. \quad (814)$$

$$= \mathcal{A}_i(0) + \mathcal{A}_i(-w) e^{iw\tau} + \mathcal{A}_i(w) e^{-iw\tau} \quad (815)$$

Here  $w = \lambda_+ - \lambda_-$ . Comparing the RHS of the equations (792) and the explicit expression for  $\widetilde{A}_i(\tau)$  in (800), we obtain the form of the expansion matrices of the Fourier decomposition for a general  $2 \times 2$  matrix:

$$\mathcal{A}_i(0) = \langle + | A_i(\tau) | + \rangle | + \rangle \langle + | + \langle - | A_i(\tau) | - \rangle | - \rangle \langle - |, \quad (816)$$

$$\mathcal{A}_i(-w) = \langle + | A_i(\tau) | - \rangle | + \rangle \langle - |, \quad (817)$$

$$\mathcal{A}_i(w) = \langle - | A_i(\tau) | + \rangle | - \rangle \langle + |. \quad (818)$$

For a decomposition of the interaction Hamiltonian in terms of Hermitian operators, i.e.  $\widetilde{A}_i(\tau) = \widetilde{A}_i^\dagger(\tau)$  and  $\widetilde{B}_i(\tau) = \widetilde{B}_i^\dagger(\tau)$  we can use the equation (792) to write the master equation in the following neater form:

$$\frac{d\overline{\rho_S}(t)}{dt} = -i [\overline{H_S}(t), \overline{\rho_S}(t)] - \sum_{ij} \int_0^t d\tau C_i(t) C_j(t-\tau) \left( \mathcal{B}_{ij}(\tau) \left[ A_i, \widetilde{A_j}(t-\tau, t) \overline{\rho_S}(t) \right] + \mathcal{B}_{ji}(-\tau) \left[ \overline{\rho_S}(t) \widetilde{A_j}(t-\tau, t), A_i \right] \right) \quad (819)$$

$$= -i [\overline{H_S}(t), \overline{\rho_S}(t)] - \sum_{ijww'} \int_0^t d\tau C_i(t) C_j(t-\tau) \left( \mathcal{B}_{ij}(\tau) \left[ A_i, e^{i\tau w(t-\tau)} e^{-it(w(t-\tau)-w'(t))} \mathcal{A}_j(w(t-\tau), w'(t)) \overline{\rho_S}(t) \right] \right. \quad (820)$$

$$\left. - \mathcal{B}_{ji}(-\tau) \left[ A_i, \overline{\rho_S}(t) e^{i\tau w(t-\tau)} e^{-it(w(t-\tau)-w'(t))} \mathcal{A}_j(w(t-\tau), w'(t)) \right] \right) \quad (821)$$

Given that  $\mathcal{A}_j(w(t-\tau), w'(t)) = \mathcal{A}_j^\dagger(-w(t-\tau), -w'(t))$  from the Fourier decomposition (792) then we can re-arrange the precedent sum in the following way with the trace respect to the bath:

$$\mathcal{B}_{ij}(\tau) = \text{Tr}_B \left( \widetilde{B_i}(t) \widetilde{B_j}(s) \rho_B \right) \quad (822)$$

$$= \text{Tr}_B \left( \widetilde{B_i}(\tau) \widetilde{B_j}(0) \rho_B \right). \quad (823)$$

Let's define:

$$\mathcal{A}_j(w(t-\tau), w'(t)) = \mathcal{A}_{jww'}(t-\tau, t) \quad (824)$$

The master equation can be re-written in the following form:

$$\frac{d\overline{\rho_S}(t)}{dt} = -i [\overline{H_S}(t), \overline{\rho_S}(t)] - \sum_{ijww'} \int_0^t d\tau C_i(t) C_j(t-\tau) \mathcal{B}_{ij}(\tau) \left[ A_i, e^{i\tau w(t-\tau)} e^{-it(w(t-\tau)-w'(t))} \mathcal{A}_{jww'}(t-\tau, t) \overline{\rho_S}(t) \right] \quad (825)$$

$$+ \sum_{ijww'} \mathcal{B}_{ji}(-\tau) \left[ A_i, \overline{\rho_S}(t) e^{i\tau w(t-\tau)} e^{-it(w(t-\tau)-w'(t))} \mathcal{A}_{jww'}(t-\tau, t) \right] \quad (826)$$

$$= -i [\overline{H_S}(t), \overline{\rho_S}(t)] - \sum_{ijww'} \int_0^t d\tau C_i(t) C_j(t-\tau) \mathcal{B}_{ij}(\tau) \left[ A_i, e^{i\tau w(t-\tau)} e^{-it(w(t-\tau)-w'(t))} \mathcal{A}_{jww'}(t-\tau, t) \overline{\rho_S}(t) \right] \quad (827)$$

$$+ \sum_{ijww'} \mathcal{B}_{ji}(-\tau) \left[ A_i, \overline{\rho_S}(t) e^{-i\tau w(t-\tau)} e^{it(w(t-\tau)-w'(t))} \mathcal{A}_{jww'}(t-\tau, t) \right] \quad (828)$$

$$= -i [\overline{H_S}(t), \overline{\rho_S}(t)] - \sum_{ijww'} \int_0^t d\tau C_i(t) C_j(t-\tau) \mathcal{B}_{ij}(\tau) \left[ A_i, e^{i\tau w(t-\tau)} e^{-it(w(t-\tau)-w'(t))} \mathcal{A}_{jww'}(t-\tau, t) \overline{\rho_S}(t) \right] \quad (829)$$

$$+ \sum_{ijww'} \mathcal{B}_{ji}(-\tau) \left[ A_i, \overline{\rho_S}(t) e^{-i\tau w(t-\tau)} e^{it(w(t-\tau)-w'(t))} \mathcal{A}_{jww'}(t-\tau, t) \right] \quad (830)$$

$$= -i [\overline{H_S}(t), \overline{\rho_S}(t)] - \sum_{ijww'} \int_0^t d\tau C_i(t) C_j(t-\tau) \mathcal{B}_{ij}(\tau) \left[ A_i, e^{i\tau w(t-\tau)} e^{-it(w(t-\tau)-w'(t))} \mathcal{A}_{jww'}(t-\tau, t) \overline{\rho_S}(t) \right] \quad (831)$$

$$- \mathcal{B}_{ji}(-\tau) \left[ A_i, \overline{\rho_S}(t) e^{-i\tau w(t-\tau)} e^{it(w(t-\tau)-w'(t))} \mathcal{A}_{jww'}(t-\tau, t) \right] \quad (832)$$

$$= -i [\overline{H_S}(t), \overline{\rho_S}(t)] - \sum_{ijww'} \int_0^t d\tau C_i(t) C_j(t-\tau) \text{Tr}_B \left( \left[ A_i, \widetilde{B_i}(\tau) \widetilde{B_j}(0) \rho_B e^{i\tau w(t-\tau)} e^{-it(w(t-\tau)-w'(t))} \mathcal{A}_{jww'}(t-\tau, t) \overline{\rho_S}(t) \right] \right) \quad (833)$$

$$- \left[ A_i, \widetilde{B_j}(-\tau) \widetilde{B_i}(0) \rho_B \overline{\rho_S}(t) e^{-i\tau w(t-\tau)} e^{it(w(t-\tau)-w'(t))} \mathcal{A}_{jww'}(t-\tau, t) \right] \quad (834)$$

Given that if we define:

$$D_{ijww'}(t-\tau, t) = C_i(t) C_j(t-\tau) \mathcal{B}_{ij}(\tau) e^{i\tau w(t-\tau)} e^{-it(w(t-\tau)-w'(t))} \mathcal{A}_{jww'}(t-\tau, t) \quad (835)$$

then

$$D_{ijww'}^\dagger(t-\tau, t) = \left( C_i(t) C_j(t-\tau) \mathcal{B}_{ij}(\tau) e^{i\tau w(t-\tau)} e^{-it(w(t-\tau)-w'(t))} \mathcal{A}_{jww'}(t-\tau, t) \right)^\dagger \quad (836)$$

$$= \mathcal{B}_{ij}^*(\tau) C_i(t) C_j(t-\tau) e^{-i\tau w(t-\tau)} e^{it(w(t-\tau)-w'(t))} \mathcal{A}_{jww'}^\dagger(t-\tau, t) \quad (837)$$

We used the fact that  $C_i(t), C_j(t - \tau)$  are real. Now let's consider the following trace recalling that  $\text{Tr}(A)^* = \text{Tr}(A^\dagger)$  so:

$$\text{Tr}_B \left( \widetilde{B}_j(-\tau) \widetilde{B}_i(0) \rho_B \right) = \text{Tr}_B \left( e^{-i\tau H_B(\tau)} B_j e^{i\tau H_B(\tau)} B_i \rho_B \right) \quad (838)$$

$$= \text{Tr}_B \left( B_j e^{i\tau H_B(\tau)} B_i \rho_B e^{-i\tau H_B(\tau)} \right) \text{ (by cyclic permutivity of trace)} \quad (839)$$

$$= \text{Tr}_B \left( B_j e^{i\tau H_B(\tau)} B_i e^{-i\tau H_B(\tau)} \rho_B \right) \text{ (by commutativity of } e^{-i\tau H_B(\tau)} \text{ and } \rho_B) \quad (840)$$

$$= \text{Tr}_B \left( B_j \widetilde{B}_i(\tau) \rho_B \right) \text{ (by definition of time evolution)} \quad (841)$$

$$= \text{Tr}_B \left( B_j \widetilde{B}_i(\tau) \rho_B \right) \quad (842)$$

$$= \text{Tr}_B \left( \rho_B B_j \widetilde{B}_i(\tau) \right) \quad (843)$$

$$= \text{Tr}_B \left( \left( \widetilde{B}_i(\tau) B_j \rho_B \right)^\dagger \right) \text{ (by definition of adjoint)} \quad (844)$$

$$= \text{Tr}_B \left( \widetilde{B}_i(\tau) B_j \rho_B \right)^* \quad (845)$$

$$= \mathcal{B}_{ij}^*(\tau) \quad (846)$$

So we can write the master equation like:

$$\frac{d\overline{\rho_S}(t)}{dt} = -i[\overline{H_S}(t), \overline{\rho_S}(t)] - \sum_{ijww'} \int_0^t d\tau C_i(t) C_j(t - \tau) \left( \mathcal{B}_{ij}(\tau) \left[ A_i, e^{i\tau w(t - \tau)} e^{-it(w(t - \tau) - w'(t))} \mathcal{A}_j(w(t - \tau), w'(t)) \overline{\rho_S}(t) \right] \right. \quad (847)$$

$$\left. - \mathcal{B}_{ij}^*(\tau) \left[ A_i, \overline{\rho_S}(t) e^{-i\tau w(t - \tau)} e^{it(w(t - \tau) - w'(t))} \mathcal{A}_j^\dagger(w(t - \tau), w'(t)) \right] \right) \quad (848)$$

$$= -i[\overline{H_S}(t), \overline{\rho_S}(t)] - \sum_{ijww'} \int_0^t d\tau \left( [A_i, D_{ijww'}(t - \tau, t) \overline{\rho_S}(t)] - [A_i, \overline{\rho_S}(t) D_{ijww'}^\dagger(t - \tau, t)] \right) \quad (849)$$

Let's define the response matrix in the following way.

$$\mathcal{D}_{ijww'}(t) = \int_0^t d\tau D_{ijww'}(t - \tau, t) \quad (850)$$

Then the master equation can be written as:

$$\frac{d\overline{\rho_S}(t)}{dt} = -i[\overline{H_S}(t), \overline{\rho_S}(t)] - \sum_{ijww'} \left( [A_i, \mathcal{D}_{ijww'}(t) \overline{\rho_S}(t)] - [A_i, \overline{\rho_S}(t) \mathcal{D}_{ijww'}^\dagger(t)] \right) \quad (851)$$

If we extend the upper limit of integration to  $\infty$  in the equation (850) then the system will be independent of any preparation at  $t = 0$ , so the evolution of the system will depend only on its present state as expected in the Markovian approximation.

Applying the inverse transformation we will obtain that:

$$e^{-V} \frac{d\overline{\rho_S}(t)}{dt} e^V = \frac{d(e^{-V} \overline{\rho_S} e^V)}{dt} \quad (852)$$

$$= \frac{d\rho_S}{dt} \quad (853)$$

$$= -ie^{-V} [\overline{H_S}(t), \overline{\rho_S}(t)] e^V - \sum_{ijww'} \int_0^t d\tau \left( e^{-V} [A_i, D_{ijww'}(t - \tau, t) \overline{\rho_S}(t)] e^V - e^{-V} [A_i, \overline{\rho_S}(t) D_{ijww'}^\dagger(t - \tau, t)] e^V \right). \quad (854)$$

For a product we have the following:

$$e^{-V} \overline{AB} e^V = e^{-V} \overline{A} \overline{B} e^V \quad (855)$$

$$= e^{-V} \overline{A} e^V e^{-V} \overline{B} e^V \quad (856)$$

$$= (e^{-V} \overline{A} e^V) (e^{-V} \overline{B} e^V) \quad (857)$$

$$= \overline{AB}. \quad (858)$$

We can use this to prove the following property for the inverse transformation of a commutator:

$$e^{-V} [\overline{A}, \overline{B}] e^V = e^{-V} \overline{(AB - BA)} e^V \quad (859)$$

$$= e^{-V} \overline{AB} e^V - e^{-V} \overline{BA} e^V \quad (860)$$

$$= \overline{AB} - \overline{BA} \quad (861)$$

$$= [\overline{A}, \overline{B}]. \quad (862)$$

So we will obtain that

$$\frac{d\rho_S}{dt} = -ie^{-V} [\overline{H_S}(t), \overline{\rho_S}(t)] e^V - e^{-V} \sum_{ijww'} \left( [A_i, \mathcal{D}_{ijww'}(t) \overline{\rho_S}(t)] - [A_i, \overline{\rho_S}(t) \mathcal{D}_{ijww'}^\dagger(t)] \right) e^V \quad (863)$$

$$= -ie^{-V} [\overline{H_S}(t), \overline{\rho_S}(t)] e^V - \sum_{ijww'} \left( e^{-V} [A_i, \mathcal{D}_{ijww'}(t) \overline{\rho_S}(t)] e^V - e^{-V} [A_i, \overline{\rho_S}(t) \mathcal{D}_{ijww'}^\dagger(t)] e^V \right) \quad (864)$$

$$= -i [H_S(t), \rho_S(t)] - \sum_{ijww'} \left( [e^{-V} A_i e^V, e^{-V} \mathcal{D}_{ijww'}(t) \overline{\rho_S}(t) e^V] - [e^{-V} A_i e^V, e^{-V} \overline{\rho_S}(t) \mathcal{D}_{ijww'}^\dagger(t) e^V] \right) \quad (865)$$

$$= -i [H_S(t), \rho_S(t)] - \sum_{ijww'} \left( [e^{-V} A_i e^V, e^{-V} \mathcal{D}_{ijww'}(t) e^V e^{-V} \overline{\rho_S}(t) e^V] - [e^{-V} A_i e^V, e^{-V} \overline{\rho_S}(t) e^V e^{-V} \mathcal{D}_{ijww'}^\dagger(t) e^V] \right) \quad (866)$$

$$= -i [H_S(t), \rho_S(t)] - \sum_{ijww'} \left( [e^{-V} A_i e^V, e^{-V} \mathcal{D}_{ijww'}(t) e^V \rho_S(t)] - [e^{-V} A_i e^V, \rho_S(t) e^{-V} \mathcal{D}_{ijww'}^\dagger(t) e^V] \right). \quad (867)$$

## V. LIMIT CASES

In order to show the plausibility of the master equation (851) for a time-dependent Hamiltonian we will show that this equation reproduces the following cases under certain limits conditions that will be pointed in each subsection.

### A. Time-independent variational quantum master equation

At first let's show that the master equation (851) reproduces the results of the reference [1], for the latter case we have that  $i, j \in \{1, 2, 3\}$  and  $\omega \in (0, \pm\eta)$ . The Hamiltonian of the system considered in this reference written in the same basis than the Hamiltonian (1) is given by:

$$H = \left( \delta + \sum_{\mathbf{k}} g_{\mathbf{k}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) \right) |1\rangle\langle 1| + \frac{\Omega}{2} \sigma_x + \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}}. \quad (868)$$

After performing the transformation (24) on the Hamiltonian (868) it's possible to split that result in the following set of Hamiltonians:

$$\overline{H_S} = (\delta + R) |1\rangle\langle 1| + \frac{\Omega_r}{2} \sigma_x, \quad (869)$$

$$\overline{H_I} = B_z |1\rangle\langle 1| + \frac{\Omega}{2} (B_x \sigma_x + B_y \sigma_y), \quad (870)$$

$$H_B = \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}}. \quad (871)$$



The Hamiltonian (869) differs from the transformed Hamiltonian  $H_S$  of the reference written like  $H_S = \frac{R}{2}\mathbb{I} + \frac{\epsilon}{2}\sigma_z + \frac{\Omega_r}{2}\sigma_x$  by a term proportional to the identity, this can be seen in the following way taking  $\epsilon = \delta + R$

$$(\delta + R) |1\rangle\langle 1| - \frac{\delta}{2}\mathbb{I} = \left(\frac{\delta}{2} + R\right) |1\rangle\langle 1| - \frac{\delta}{2} |0\rangle\langle 0| \quad (872)$$

$$= \frac{R}{2}\mathbb{I} + \frac{\delta + R}{2}\sigma_z \quad (873)$$

$$= \frac{R}{2}\mathbb{I} + \frac{\epsilon}{2}\sigma_z. \quad (874)$$

In this Hamiltonian we can write  $A_i = \sigma_x$ ,  $A_2 = \sigma_y$  and  $A_3 = \frac{I+\sigma_z}{2} = |1\rangle\langle 1|$  with  $\sigma_z = |1\rangle\langle 1| - |0\rangle\langle 0|$ . In order to find the decomposition matrices of the Fourier decomposition let's obtain the eigenvalues and eigenvectors of the matrix  $\overline{H_S}$ . Given that  $\overline{H_S} = \frac{R}{2}\mathbb{I} + \frac{\epsilon}{2}\sigma_z + \frac{\Omega_r}{2}\sigma_x$  then  $\text{Tr}(\overline{H_S}) = R$  and  $\text{Det}(\overline{H_S}) = \frac{R^2 - \epsilon^2}{4} - \frac{\Omega_r^2}{4}$  then by the Caley-Hamilton theorem then we will have that the equations of the eigenvalues and it's values are given by::

$$0 = \lambda^2 - R\lambda + \frac{R^2 - \epsilon^2 - \Omega_r^2}{4}, \quad (875)$$

$$\lambda_{\pm} = \frac{R \pm \sqrt{(-R)^2 - 4\left(\frac{R^2 - \epsilon^2 - \Omega_r^2}{4}\right)}}{2} \quad (876)$$

$$= \frac{R \pm \sqrt{R^2 - (R^2 - \epsilon^2 - \Omega_r^2)}}{2} \quad (877)$$

$$= \frac{R \pm \sqrt{\epsilon^2 + \Omega_r^2}}{2} \quad (878)$$

$$\eta = \sqrt{\epsilon^2 + \Omega_r^2}, \quad (879)$$

$$\lambda_{\pm} = \frac{R \pm \eta}{2}. \quad (880)$$

For  $\lambda_+ = \frac{R+\eta}{2}$  we will obtain the associated eigenvector like:

$$\begin{pmatrix} \frac{R}{2} - \frac{\epsilon}{2} - \frac{R+\eta}{2} & \frac{\Omega_r}{2} \\ \frac{\Omega_r}{2} & \frac{R}{2} + \frac{\epsilon}{2} - \frac{R+\eta}{2} \end{pmatrix} = \begin{pmatrix} -\frac{\epsilon}{2} - \frac{\eta}{2} & \frac{\Omega_r}{2} \\ \frac{\Omega_r}{2} & \frac{\epsilon}{2} - \frac{\eta}{2} \end{pmatrix}. \quad (881)$$

so the eigenvector  $|+\rangle = a|0\rangle + b|1\rangle$  satisfies  $-\frac{\epsilon+\eta}{2}a + \frac{\Omega_r}{2}b = 0$ , so  $a = \frac{\Omega_r}{\epsilon+\eta}b$  then the normalized eigenvector is  $|+\rangle = \frac{\Omega_r}{\sqrt{(\epsilon+\eta)^2 + \Omega_r^2}}|0\rangle + \frac{\epsilon+\eta}{\sqrt{(\epsilon+\eta)^2 + \Omega_r^2}}|1\rangle$  with  $\sin(\theta) = \frac{\Omega_r}{\sqrt{(\epsilon+\eta)^2 + \Omega_r^2}}$  and  $\cos(\theta) = \frac{\epsilon+\eta}{\sqrt{(\epsilon+\eta)^2 + \Omega_r^2}}$ . The vector is written in reduced way like  $|+\rangle = \sin(\theta)|0\rangle + \cos(\theta)|1\rangle$ .

For  $\lambda_- = \frac{R-\eta}{2}$  we will obtain the associated eigenvector like:

$$\begin{pmatrix} \frac{R}{2} - \frac{\epsilon}{2} - \frac{R-\eta}{2} & \frac{\Omega_r}{2} \\ \frac{\Omega_r}{2} & \frac{R}{2} + \frac{\epsilon}{2} - \frac{R-\eta}{2} \end{pmatrix} = \begin{pmatrix} -\frac{\epsilon}{2} + \frac{\eta}{2} & \frac{\Omega_r}{2} \\ \frac{\Omega_r}{2} & \frac{\epsilon}{2} + \frac{\eta}{2} \end{pmatrix}. \quad (882)$$

so the eigenvector  $|+\rangle = a|0\rangle + b|1\rangle$  satisfies  $\frac{\Omega_r}{2}a + \frac{\epsilon+\eta}{2}b = 0$ , so  $a = -\frac{\epsilon+\eta}{\Omega_r}b$  then the normalized eigenvector is  $|-\rangle = \frac{\epsilon+\eta}{\sqrt{(\epsilon+\eta)^2 + \Omega_r^2}}|0\rangle - \frac{\Omega_r}{\sqrt{(\epsilon+\eta)^2 + \Omega_r^2}}|1\rangle$ . The vector is written in reduced way like  $|-\rangle = \cos(\theta)|0\rangle - \sin(\theta)|1\rangle$ . Summarizing these results we can write:

$$\lambda_+ = \frac{\epsilon + \eta}{2}, \quad (883)$$

$$\lambda_- = \frac{\epsilon - \eta}{2}, \quad (884)$$

$$|+\rangle = \sin(\theta) |0\rangle + \cos(\theta) |1\rangle, \quad (885)$$

$$|-\rangle = \cos(\theta) |0\rangle - \sin(\theta) |1\rangle, \quad (886)$$

$$\sin(\theta) = \frac{\Omega_r}{\sqrt{(\epsilon + \eta)^2 + \Omega_r^2}}, \quad (887)$$

$$\cos(\theta) = \frac{\epsilon + \eta}{\sqrt{(\epsilon + \eta)^2 + \Omega_r^2}}. \quad (888)$$

This result is plausible because in the paper [1] we have that:

$$\theta = \frac{1}{2} \tan^{-1} \left( \frac{\Omega_r}{\epsilon} \right). \quad (889)$$

We can obtain the value of  $\tan(\theta)$  through the following trigonometry identity for  $x = \tan^{-1} \left( \frac{\Omega_r}{\epsilon} \right)$ .

$$\tan \left( \frac{x}{2} \right) = \frac{\sin(x)}{\cos(x) + 1}. \quad (890)$$

So the value of  $\tan(\theta)$  using (890) is equal to:

$$\tan(\theta) = \frac{\frac{\Omega_r}{\sqrt{(\epsilon + \eta)^2 + \Omega_r^2}}}{\frac{\epsilon}{\sqrt{(\epsilon + \eta)^2 + \Omega_r^2}} + 1} \quad (891)$$

$$= \frac{\frac{\Omega_r}{\sqrt{(\epsilon + \eta)^2 + \Omega_r^2}}}{\frac{\epsilon + \sqrt{(\epsilon + \eta)^2 + \Omega_r^2}}{\sqrt{(\epsilon + \eta)^2 + \Omega_r^2}}} \quad (892)$$

$$= \frac{\Omega_r}{\epsilon + \eta}. \quad (893)$$

This proves our assertion.

Using this basis we can find the decomposition matrices using the equations (817)-(818) and the fact that  $|+\rangle = \sin(\theta) |0\rangle + \cos(\theta) |1\rangle = \begin{pmatrix} \sin(\theta) \\ \cos(\theta) \end{pmatrix}$  and  $|-\rangle = \cos(\theta) |0\rangle - \sin(\theta) |1\rangle = \begin{pmatrix} \cos(\theta) \\ -\sin(\theta) \end{pmatrix}$  with  $\sin(\theta) = \frac{\Omega_r}{\sqrt{(\epsilon + \eta)^2 + \Omega_r^2}}$  and  $\cos(\theta) = \frac{\epsilon + \eta}{\sqrt{(\epsilon + \eta)^2 + \Omega_r^2}}$ :

$$\langle +|\sigma_x|+\rangle = \begin{pmatrix} \sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \sin(\theta) \\ \cos(\theta) \end{pmatrix} \quad (894)$$

$$= 2 \sin(\theta) \cos(\theta) \quad (895)$$

$$= \sin(2\theta), \quad (896)$$

$$\langle -|\sigma_x|-\rangle = \begin{pmatrix} \cos(\theta) & -\sin(\theta) \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \cos(\theta) \\ -\sin(\theta) \end{pmatrix} \quad (897)$$

$$= -2 \sin(\theta) \cos(\theta) \quad (898)$$

$$= -\sin(2\theta), \quad (899)$$

$$\langle -|\sigma_x|+\rangle = \begin{pmatrix} \cos(\theta) & -\sin(\theta) \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \sin(\theta) \\ \cos(\theta) \end{pmatrix} \quad (900)$$

$$= \cos^2(\theta) - \sin^2(\theta) \quad (901)$$

$$= \cos(2\theta), \quad (902)$$

$$\langle +|\sigma_y|+\rangle = \begin{pmatrix} \sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} 0 & i \\ -i & 0 \end{pmatrix} \begin{pmatrix} \sin(\theta) \\ \cos(\theta) \end{pmatrix} \quad (903)$$

$$= i \sin(\theta) \cos(\theta) - i \sin(\theta) \cos(\theta) \quad (904)$$

$$= 0, \quad (905)$$

$$\langle -|\sigma_y|-\rangle = \begin{pmatrix} \cos(\theta) & -\sin(\theta) \end{pmatrix} \begin{pmatrix} 0 & i \\ -i & 0 \end{pmatrix} \begin{pmatrix} \cos(\theta) \\ -\sin(\theta) \end{pmatrix} \quad (906)$$

$$= i \sin(\theta) \cos(\theta) - i \sin(\theta) \cos(\theta) \quad (907)$$

$$= 0, \quad (908)$$

$$\langle -|\sigma_y|+\rangle = \begin{pmatrix} \cos(\theta) & -\sin(\theta) \end{pmatrix} \begin{pmatrix} 0 & i \\ -i & 0 \end{pmatrix} \begin{pmatrix} \sin(\theta) \\ \cos(\theta) \end{pmatrix} \quad (909)$$

$$= i \cos^2(\theta) + i \sin^2(\theta) \quad (910)$$

$$= i. \quad (911)$$

$$\langle +|\frac{1+\sigma_z}{2}|+\rangle = \begin{pmatrix} \sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \sin(\theta) \\ \cos(\theta) \end{pmatrix} \quad (912)$$

$$= \cos(\theta) \cos(\theta) \quad (913)$$

$$= \cos^2(\theta), \quad (914)$$

$$\langle -|\frac{1+\sigma_z}{2}|-\rangle = \begin{pmatrix} \cos(\theta) & -\sin(\theta) \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(\theta) \\ -\sin(\theta) \end{pmatrix} \quad (915)$$

$$= \sin(\theta) \sin(\theta) \quad (916)$$

$$= \sin^2(\theta), \quad (917)$$

$$\langle -|\frac{1+\sigma_z}{2}|+\rangle = \begin{pmatrix} \cos(\theta) & -\sin(\theta) \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \sin(\theta) \\ \cos(\theta) \end{pmatrix} \quad (918)$$

$$= -\sin(\theta) \cos(\theta) \quad (919)$$

$$= -\sin(\theta) \cos(\theta). \quad (920)$$

Composing the parts shown give us the Fourier decomposition matrices for this case:

$$A_1(0) = \sin(2\theta) (|+\rangle\langle+| - |-\rangle\langle-|), \quad (921)$$

$$A_1(\eta) = \cos(2\theta) |-\rangle\langle+|, \quad (922)$$

$$A_2(0) = 0, \quad (923)$$

$$A_2(\eta) = i|-\rangle\langle+|, \quad (924)$$

$$A_3(0) = \cos^2(\theta) |+\rangle\langle+| + \sin^2(\theta) |-\rangle\langle-|, \quad (925)$$

$$A_3(\eta) = -\sin(\theta) \cos(\theta) |-\rangle\langle+|. \quad (926)$$

Now to prove the fact that the model of the “Time-independent variational quantum master equation” is a special case the master equation (854) we need to take account of the time-independence of the hamiltonian of this system. From this perspective is possible to show that for the equation (835) is equivalent to:

$$\mathcal{D}_{ijww'}(t) = \int_0^t d\tau D_{ijww'}(t-\tau, t) \quad (927)$$

$$= \int_0^t d\tau C_i(t) C_j(t-\tau) \Lambda_{ij}(\tau) e^{i\tau w(t-\tau)} e^{-it(w(t-\tau)-w'(t))} \mathcal{A}_j(w(t-\tau), w'(t)) \quad (928)$$

$$= \int_0^t d\tau C_i(t) C_j(t-\tau) \Lambda_{ij}(\tau) e^{i\tau w} e^{-it(w-w')} \mathcal{A}_j(w, w'). \quad (929)$$

Now to make comparisons between the model obtained and the model of the system under discussion we will define that the correlation functions of the reference [1] denoted by  $\Lambda'_{ij}(\tau)$  relate with the correlation functions defined in the equation (396) in the following way:

$$\Lambda'_{ij}(\tau) = C_i(t) C_j(t-\tau) \Lambda_{ij}(\tau). \quad (930)$$

So the response matrix can be rewritten as:

$$\mathcal{D}_{ijww'}(t) = \left( \int_0^t d\tau \Lambda'_{ij}(\tau) e^{i\tau w} e^{-it(w-w')} \right) \mathcal{A}_j(w, w') \quad (931)$$

Let's define the response function like:

$$K_{ij}(w, w', t) = \int_0^t C_i(t) C_j(t-\tau) \Lambda_{ij}(\tau) e^{i\tau w} e^{-it(w-w')} d\tau \quad (932)$$

$$= \int_0^t \Lambda'_{ij}(\tau) e^{i\tau w} e^{-it(w-w')} d\tau \quad (933)$$

$$= K_{ijww'}(t). \quad (934)$$

Then we have the following equivalence:

$$\mathcal{D}_{ijww'}(t) = K_{ijww'}(t) \mathcal{A}_j(w, w') \quad (935)$$

$$= K_{ijww'}(t) \mathcal{A}_{jww'} \quad (936)$$

We can proof that

$$\frac{d\overline{\rho_S}(t)}{dt} = -i [\overline{H_S}(t), \overline{\rho_S}(t)] - \sum_{ijww'} \left( [A_i, \mathcal{D}_{ijww'}(t) \overline{\rho_S}(t)] - [A_i, \overline{\rho_S}(t) \mathcal{D}_{ijww'}^\dagger(t)] \right) \quad (937)$$

$$= -i [\overline{H_S}(t), \overline{\rho_S}(t)] - \sum_{ijww'} \left( [A_i, K_{ijww'}(t) \mathcal{A}_{jww'} \overline{\rho_S}(t)] - [A_i, \overline{\rho_S}(t) K_{ijww'}^*(t) \mathcal{A}_{jww'}^\dagger] \right) \quad (938)$$

$$= -i [\overline{H_S}(t), \overline{\rho_S}(t)] - \sum_{ijww'} \left( K_{ijww'}(t) [A_i, \mathcal{A}_{jww'} \overline{\rho_S}(t)] - K_{ijww'}^*(t) [A_i, \overline{\rho_S}(t) \mathcal{A}_{jww'}^\dagger] \right) \quad (939)$$

$$= -i [\overline{H_S}(t), \overline{\rho_S}(t)] - \sum_{ijww'} \left( (K_{ijww'}^{\Re}(t) + i K_{ijww'}^{\Im}(t)) [A_i, \mathcal{A}_{jww'} \overline{\rho_S}(t)] - (K_{ijww'}^{\Re}(t) - i K_{ijww'}^{\Im}(t)) [A_i, \overline{\rho_S}(t) \mathcal{A}_{jww'}^\dagger] \right) \quad (940)$$

$$= -i [\overline{H_S}(t), \overline{\rho_S}(t)] - \sum_{ijww'} K_{ijww'}^{\Re}(t) [A_i, \mathcal{A}_{jww'} \overline{\rho_S}(t) - \overline{\rho_S}(t) \mathcal{A}_{jww'}^\dagger] - i \sum_{ijww'} K_{ijww'}^{\Im}(t) [A_i, \mathcal{A}_{jww'} \overline{\rho_S}(t) + \overline{\rho_S}(t) \mathcal{A}_{jww'}^\dagger] \quad (941)$$

Using the notation of the master equation (851), we can say that  $C_1(t) = \frac{\Omega}{2} = C_2(t)$  and  $C_3(t) = 1$ , being  $\Omega$  a constant. Furthermore given that  $\overline{H_S}$  is time-independent then  $B(t) = B$ . Taking the equations (741)-(751) we find that the correlation functions of the reference [1] written in terms of the RHS of the equation (396) are equal to:

$$\Lambda'_{11}(\tau) = \left( \frac{\Omega}{2} \right)^2 \text{Tr}_B \left( \widetilde{B}_1(\tau) \widetilde{B}_1(0) \rho_B \right) \quad (942)$$

$$= \frac{\Omega_r^2}{8} \left( e^{\phi(\tau)} + e^{-\phi(\tau)} - 2 \right), \quad (943)$$

$$\Lambda'_{22}(\tau) = \left( \frac{\Omega}{2} \right)^2 \text{Tr}_B \left( \widetilde{B}_2(\tau) \widetilde{B}_2(0) \rho_B \right) \quad (944)$$

$$= \frac{\Omega_r^2}{8} \left( e^{\phi(\tau)} + e^{-\phi(\tau)} \right), \quad (945)$$

$$\Lambda'_{33}(\tau) = \int_0^\infty d\omega J(\omega) (1 - F(\omega))^2 G_+(\tau), \quad (946)$$

$$\Lambda'_{32}(\tau) = \frac{\Omega_r}{2} \int_0^\infty d\omega \frac{J(\omega)}{\omega} F(\omega) (1 - F(\omega)) iG_-(\tau), \quad (947)$$

$$\Lambda'_{32}(\tau) = -\Lambda'_{23}(\tau), \quad (948)$$

$$\Lambda'_{12}(\tau) = \Lambda'_{21}(\tau) \quad (949)$$

$$= \Lambda'_{13}(\tau) \quad (950)$$

$$= \Lambda'_{31}(\tau) \quad (951)$$

$$= 0. \quad (952)$$

Finally taking the Hamiltonian (868) and given that to reproduce this Hamiltonian we need to impose in (5) that  $V_{10}(t) = \frac{\Omega}{2}$ ,  $\varepsilon_0(t) = 0$  and  $\varepsilon_1(t) = \delta$ , then we obtain that  $\text{Det}(\overline{H_S}) = -\frac{\Omega_r^2}{4}$ ,  $\text{Tr}(\overline{H_S}) = \epsilon$ . Now  $\eta = \sqrt{\epsilon^2 + \Omega_r^2}$  and using the equation (336) we have that:

$$f_k = \frac{g_k \left( 1 - \frac{\epsilon \tanh\left(\frac{\beta\eta}{2}\right)}{\eta} \right)}{1 - \frac{\tanh\left(\frac{\beta\eta}{2}\right)}{\eta} \left( \epsilon - \frac{\Omega_r^2 \coth\left(\frac{\beta\omega_k}{2}\right)}{2\omega_k} \right)} \quad (953)$$

$$= \frac{g_k \left( 1 - \frac{\epsilon \tanh\left(\frac{\beta\eta}{2}\right)}{\eta} \right)}{1 - \frac{\epsilon \tanh\left(\frac{\beta\eta}{2}\right)}{\eta} \left( 1 - \frac{\Omega_r^2 \coth\left(\frac{\beta\omega_k}{2}\right)}{2\epsilon\omega_k} \right)}. \quad (954)$$

This shows that the expression obtained reproduces the variational parameters of the time-independent model of the reference. In general we can see that the time-independent model studied can be reproduced using the master equation (432) under a time-independent approach providing similar results.

Given that the Hamiltonian of this system is time-independent, then  $U(t)U^\dagger(t-\tau) = U(\tau)$ . From the equation (851) and using the fact that

$$\widetilde{A_j}(t-\tau, t) = U(\tau) A_j U(-\tau) \quad (955)$$

$$= \sum_w e^{iw\tau} \mathcal{A}_j(-w) \quad (956)$$

$$= \sum_w e^{-iw\tau} \mathcal{A}_j(w). \quad (957)$$

because the matrices  $U(t)$  and  $U(t-\tau)$  commute from the fact that  $H_S(t)$  and  $H_S(t-\tau)$  commute as well for time independent Hamiltonians. The master equation is equal to:

$$\frac{d\bar{\rho}_S(t)}{dt} = -i[H_S(t), \bar{\rho}_S(t)] - \frac{1}{2} \sum_{ij} \sum_w \gamma_{ij}(w, t) \left[ A_i, \mathcal{A}_j(w) \bar{\rho}_S(t) - \bar{\rho}_S(t) \mathcal{A}_j^\dagger(w) \right] \quad (958)$$

$$- \sum_{ij} \sum_w S_{ij}(w, t) \left[ A_i, \mathcal{A}_j(w) \bar{\rho}_S(t) + \bar{\rho}_S(t) \mathcal{A}_j^\dagger(w) \right]. \quad (959)$$

where  $\mathcal{A}_j^\dagger(w) = \mathcal{A}_j(-w)$ , as we can see the equation (959) contains the rates and energy shifts  $\gamma_{ij}(w, t) = 2K_{ij}^{\mathcal{R}}(w, t)$  and  $S_{ij}(w, t) = K_{ij}^{\mathcal{S}}(w, t)$ , respectively, defined in terms of the response functions

$$K_{ij}^{\mathcal{S}}(w, t) = \int_0^t \Lambda'_{ij}(\tau) e^{iw\tau} d\tau.$$

The fact  $\mathcal{A}_j^\dagger(w) = \mathcal{A}_j(-w)$  can be verified directly for a  $2 \times 2$  matrix. given that  $\overline{H_S}$  is independent of time then we have that:

$$e^{i\overline{H_S}(t-\tau)} = e^{i(\lambda_+|+\rangle\langle+| + \lambda_-|-\rangle\langle-|)(t-\tau)} \quad (960)$$

$$= e^{i\lambda_+|+\rangle\langle+|(t-\tau)} e^{i\lambda_-|-\rangle\langle-|(t-\tau)} \quad (961)$$

$$= \left( |-\rangle\langle-| + e^{i\lambda_+(t-\tau)} |+\rangle\langle+| \right) \left( |+\rangle\langle+| + e^{i\lambda_-(t-\tau)} |-\rangle\langle-| \right) \quad (962)$$

$$= e^{i\lambda_+(t-\tau)} |+\rangle\langle+| + e^{i\lambda_-(t-\tau)} |-\rangle\langle-|. \quad (963)$$

Where  $\lambda_+, \lambda_-$  are the eigenvalues associated to the eigenvectors  $|+\rangle\langle+|, |-\rangle\langle-|$  of  $\overline{H_S}$ . Calculating the transformation (792) of (816)-(818) directly using the previous relationship we find that:

$$\widetilde{A_i(0)}(t-\tau) = (e^{i\lambda_+(t-\tau)} |+\rangle\langle+| + e^{i\lambda_-(t-\tau)} |-\rangle\langle-|) (\langle+|A_i|+\rangle |+\rangle\langle+| + \langle-|A_i|-\rangle |-\rangle\langle-|) (e^{-i\lambda_+(t-\tau)} |+\rangle\langle+| + e^{-i\lambda_-(t-\tau)} |-\rangle\langle-|) \quad (964)$$

$$= \langle+|A_i|+\rangle |+\rangle\langle+| + \langle-|A_i|-\rangle |-\rangle\langle-|, \quad (965)$$

$$\widetilde{A_i(w)}(t-\tau) = (e^{i\lambda_+(t-\tau)} |+\rangle\langle+| + e^{i\lambda_-(t-\tau)} |-\rangle\langle-|) (\langle+|A_i|-\rangle |+\rangle\langle-|) (e^{-i\lambda_+(t-\tau)} |+\rangle\langle+| + e^{-i\lambda_-(t-\tau)} |-\rangle\langle-|) \quad (966)$$

$$= \langle+|A_i|-\rangle |+\rangle\langle-| e^{iw(t-\tau)}, \quad (967)$$

$$\widetilde{A_i(-w)}(t-\tau) = (e^{i\lambda_+(t-\tau)} |+\rangle\langle+| + e^{i\lambda_-(t-\tau)} |-\rangle\langle-|) (\langle-|A_i|+\rangle |-\rangle\langle+|) (e^{-i\lambda_+(t-\tau)} |+\rangle\langle+| + e^{-i\lambda_-(t-\tau)} |-\rangle\langle-|) \quad (968)$$

$$= \langle-|A_i|+\rangle |-\rangle\langle+| e^{-iw(t-\tau)}. \quad (969)$$

Here  $w = \lambda_+ - \lambda_-$ . So we can see that for the equation (802) it's possible to deduce for this case of time-independent matrix  $\overline{H_S}$  if  $w \neq w'$  then  $A'_j(w, w') = 0$  so:

$$\widetilde{A}_j(t - \tau, t) = U(t) U^\dagger(t - \tau) A_j(t) U(t - \tau) U^\dagger(t) \quad (970)$$

$$= U(t) \left( \sum_{w(t-\tau)} e^{-i(t-\tau)w(t-\tau)} A_j(w(t-\tau)) \right) U^\dagger(t) \quad (971)$$

$$= \sum_{w(t-\tau)} e^{-i(t-\tau)w(t-\tau)} U(t) A_j(w(t-\tau)) U^\dagger(t) \quad (972)$$

$$= \sum_{w'(t), w(t-\tau)} e^{-i(t-\tau)w(t-\tau)} e^{itw'(t)} A_j(w(t-\tau), w'(t)) \quad (973)$$

$$= \sum_{w'(t), w(t-\tau)} e^{-i(t-\tau)w(t-\tau)} e^{itw'(t)} A_{jww'} \quad (974)$$

$$== \sum_{w'(t), w(t-\tau)} e^{-i(t-\tau)w(t-\tau)} e^{itw'(t)} A_j(w) \delta_{ww'} \quad (975)$$

$$= \sum_w e^{-i(t-\tau)w} e^{itw} A_j(w) \quad (976)$$

$$= \sum_w e^{i\tau w} A_j(w) \quad (977)$$

$$= U^\dagger(-\tau) A_j U(-\tau) \quad (978)$$

So using now as reference the equation (941) and  $A'_j(w, w') = 0$  we can deduce that:

$$\frac{d\overline{\rho_S}(t)}{dt} = -i[\overline{H_S}(t), \overline{\rho_S}(t)] - \sum_{ijw} K_{ij}^{\Re}(w, t) [A_i, A_j(w) \overline{\rho_S}(t) - \overline{\rho_S}(t) A_j^\dagger(w)] - i \sum_{ijw} K_{ij}^{\Im}(w, t) [A_i, A_j(w) \overline{\rho_S}(t) + \overline{\rho_S}(t) A_j^\dagger(w)] \quad (979)$$

## B. Time-dependent polaron quantum master equation

Following the reference [1], when  $\Omega_k \ll \omega_k$  then  $f_k \approx g_k$  so we recover the full polaron transformation. It means from the equation (107) that  $B_z = 0$ . The Hamiltonian studied is given by:

$$H = \left( \delta + \sum_{\mathbf{k}} \left( g_{\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{\mathbf{k}}^* b_{\mathbf{k}} \right) \right) |1\rangle\langle 1| + \frac{\Omega(t)}{2} \sigma_x + \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}}. \quad (980)$$

If  $v_{\mathbf{k}} \approx g_{\mathbf{k}}$  then  $B(\tau) = B$ , so  $B$  is independent of the time. In order to reproduce the Hamiltonian of the equation (980) using the Hamiltonian of the equation (1) we can say that  $\delta = \varepsilon_1(t)$ ,  $\varepsilon_0(t) = 0$ ,  $V_{10}(t) = \frac{\Omega(t)}{2}$ . Now given that  $v_{\mathbf{k}} \approx g_{\mathbf{k}}$  then, in this case and using the equation (225) and (236) we obtain the following transformed Hamiltonians:

$$\overline{H_S} = (\delta + R_1) |1\rangle\langle 1| + \frac{B\sigma_x}{2} \Omega(t), \quad (981)$$

$$\overline{H_I} = \frac{\Omega(t)}{2} (B_x \sigma_x + B_y \sigma_y). \quad (982)$$

In this case  $R_1 = \sum_{\mathbf{k}} \left( \omega_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} - 2 \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} g_{\mathbf{k}} \right)$  from (27) and given that  $v_{\mathbf{k}} \approx g_{\mathbf{k}}$  and  $\frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} = g_{\mathbf{k}}/\omega_{\mathbf{k}}$  then  $R_1 = \sum_{\mathbf{k}} (-\omega_{\mathbf{k}}^{-1} |g_{\mathbf{k}}|^2) = \sum_{\mathbf{k}} (-\omega_{\mathbf{k}} | \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} |^2)$  as expected, take  $\delta + R_1 = \delta'$ . If  $F(\omega_{\mathbf{k}}) = 1$  and using the equations (942)-(949) we can deduce that the only terms that survive are  $\Lambda_{11}(\tau)$  and  $\Lambda_{22}(\tau)$ . The phonon propagator for this case is:

$$\phi(\tau) = \int_0^\infty \frac{J(\omega)}{\omega^2} G_+(\tau) d\omega. \quad (983)$$

Writing  $G_+(\tau) = \coth\left(\frac{\beta\omega}{2}\right) \cos(\omega\tau) - i \sin(\omega\tau)$  so (983) can be written as:

$$\phi(\tau) = \int_0^\infty \frac{J(\omega)}{\omega^2} \left( \coth\left(\frac{\beta\omega}{2}\right) \cos(\omega\tau) - i \sin(\omega\tau) \right) d\omega. \quad (984)$$

Writing the interaction Hamiltonian (982) in the similar way to the equation (236) allow us to write  $A_1 = \sigma_x$ ,  $A_2 = \sigma_y$ ,  $B_1(t) = B_x$ ,  $B_2(t) = B_y$  and  $C_1(t) = \frac{\Omega(t)}{2} = C_2(t)$ . Now taking the equation (225) with  $\delta'|1\rangle\langle 1| = \frac{\delta'}{2}\sigma_z + \frac{\delta'}{2}\mathbb{I}$  help us to reproduce the hamiltonian of the reference [2]. Then  $\overline{H_S}$  is equal to:

$$\overline{H_S} = \frac{\delta'}{2}\sigma_z + \frac{B\sigma_x}{2}\Omega(t). \quad (985)$$

As we can see the function  $B$  is a time-independent function because we consider that  $g_k$  doesn't depend of the time. In this case the relevant correlation functions are given by:

$$\Lambda_{11}(\tau) = \text{Tr}_B \left( \widetilde{B}_1(\tau) \widetilde{B}_1(0) \rho_B \right) \quad (986)$$

$$= \frac{B^2}{2} \left( e^{\phi(\tau)} + e^{-\phi(\tau)} - 2 \right), \quad (987)$$

$$\Lambda_{22}(\tau) = \text{Tr}_B \left( \widetilde{B}_2(\tau) \widetilde{B}_2(0) \rho_B \right) \quad (988)$$

$$= \frac{B^2}{2} \left( e^{\phi(\tau)} + e^{-\phi(\tau)} \right). \quad (989)$$

These functions match with the equations  $\Lambda_x(\tau)$  and  $\Lambda_y(\tau)$  of the reference [2] and  $\Lambda_i(\tau) = \Lambda_i(-\tau)$  for  $i \in \{x, y\}$  respectively. The master equation for this section based on the equation(432) is:

$$\frac{d\rho_S(t)}{dt} = -i \left[ \frac{\delta'}{2}\sigma_z + \frac{\Omega_r(t)\sigma_x}{2}, \rho_S(t) \right] - \sum_{i=1}^2 \int_0^t d\tau \left( C_i(t) C_i(t-\tau) \Lambda_{ii}(\tau) \left[ A_i, \widetilde{A}_i(t-\tau, t) \rho_S(t) \right] \right. \quad (990)$$

$$\left. + C_i(t) C_i(t-\tau) \Lambda_{ii}(-\tau) \left[ \rho_S(t) \widetilde{A}_i(t-\tau, t), A_i \right] \right). \quad (991)$$

Replacing  $C_i(t) = \frac{\Omega(t)}{2}$  and  $\widetilde{A}_i(t-\tau, t) = \widetilde{\sigma}_i(t-\tau, t)$ , also using the equations (986) and (989) on the equation (991) we obtain that:

$$\frac{d\rho_S(t)}{dt} = -\frac{i}{2} [\delta'\sigma_z + \Omega_r(t)\sigma_x, \rho_S(t)] - \frac{\Omega(t)}{4} \int_0^t d\tau \Omega(t-\tau) ([\sigma_x, \widetilde{\sigma}_x(t-\tau, t) \rho_S(t)] \Lambda_x(\tau) \quad (992)$$

$$+ [\sigma_y, \widetilde{\sigma}_y(t-\tau, t) \rho_S(t)] \Lambda_y(\tau) + [\rho_S(t) \widetilde{\sigma}_x(t-\tau, t), \sigma_x] \Lambda_x(\tau) + [\rho_S(t) \widetilde{\sigma}_y(t-\tau, t), \sigma_y] \Lambda_y(\tau)). \quad (993)$$

As we can see  $\left[ A_j, \widetilde{A}_i(t-\tau, t) \rho_S(t) \right]^\dagger = \left[ \rho_S(t) \widetilde{A}_i(t-\tau, t), A_j \right]$ ,  $\Lambda_x(\tau) = \Lambda_x(-\tau)$  and  $\Lambda_y(\tau) = \Lambda_y(-\tau)$ , so the result obtained is the same master equation (21) of the reference [2] extended in the hermitian conjugate.

### C. Time-Dependent Weak-Coupling Limit

In order to prove that the master equation deduced reproduces the equation (S17) of the reference [3] we will impose that  $F(\omega) = 0$ , so there is no transformation in this case. As we can see from the definition (396) the only term that survives is  $\Lambda_{33}(\tau)$ . Taking  $\hbar = 1$  the Hamiltonian of the reference can be written in the form:

$$H = \Delta|1\rangle\langle 1| + \frac{\Omega(t)}{2} (|1\rangle\langle 0| + |0\rangle\langle 1|) + \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + |1\rangle\langle 1| \sum_{\mathbf{k}} \left( g_{\mathbf{k}} b_{\mathbf{k}}^\dagger + g_{\mathbf{k}}^* b_{\mathbf{k}} \right). \quad (994)$$

Using the equation (851), from the fact that the Hamiltonian is time-independent in the evolution time allow us to write:



$$\frac{d\rho_S}{dt} = -i[H_S(t), \rho_S(t)] - \frac{1}{2} \sum_w \gamma_{33}(w, t) \left[ A_3, A_3(w) \rho_S(t) - \rho_S(t) A_3^\dagger(w) \right] \quad (995)$$

$$- \sum_w S_{33}(w, t) \left[ A_3, A_3(w) \rho_S(t) + \rho_S(t) A_3^\dagger(w) \right] \Bigg). \quad (996)$$

The correlation functions are relevant if  $F(\omega) = 0$  for the weak-coupling approximation are:

$$\Lambda_{33}(\tau) = \int_0^\infty d\omega J(\omega) G_+(\tau), \quad (997)$$

$$\Lambda_{33}(-\tau) = \int_0^\infty d\omega J(\omega) G_+(-\tau). \quad (998)$$

In our case  $A_3 = \frac{\mathbb{I} + \sigma_z}{2}$ , the equation (996) can be transformed in

$$\frac{d\rho_S}{dt} = -i[H_S(t), \rho_S(t)] - \sum_w (K_{33}(w, t) [A_3, A_3(w) \rho_S(t)] + K_{33}^*(w, t) [\rho_S(t) A_3(w), A_3]). \quad (999)$$

As the paper suggest we will consider that the quantum system is in resonance, so  $\Delta = 0$  and furthermore, the relaxation time of the bath is less than the evolution time to be considered, so the frequency of the Rabi frequency of the laser can be taken as constant and equal to  $\tilde{\Omega}$ . To find the matrices  $A_3(w)$ , we have to remember that  $H_S = \frac{\Omega(t)}{2} (|1\rangle\langle 0| + |0\rangle\langle 1|)$ , this Hamiltonian using the approximation  $\tilde{\Omega}$  have the following eigenvalues and eigenvectors:

$$\lambda_+ = \frac{\tilde{\Omega}}{2}, \quad (1000)$$

$$|+\rangle = \frac{1}{\sqrt{2}} (|1\rangle + |0\rangle), \quad (1001)$$

$$\lambda_- = -\frac{\tilde{\Omega}}{2}, \quad (1002)$$

$$|-\rangle = \frac{1}{\sqrt{2}} (|0\rangle - |1\rangle). \quad (1003)$$

The elements of the decomposition matrices are:

$$\langle + | \frac{1 + \sigma_z}{2} | + \rangle = \frac{1}{2} \begin{pmatrix} 1 & 1 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (1004)$$

$$= \frac{1}{2}, \quad (1005)$$

$$\langle - | \frac{1 + \sigma_z}{2} | - \rangle = \frac{1}{2} \begin{pmatrix} 1 & -1 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ -1 \end{pmatrix} \quad (1006)$$

$$= \frac{1}{2}, \quad (1007)$$

$$\langle - | \frac{1 + \sigma_z}{2} | + \rangle = \frac{1}{2} \begin{pmatrix} 1 & -1 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (1008)$$

$$= -\frac{1}{2}. \quad (1009)$$

The decomposition matrices are

$$A_3(0) = \frac{1}{2}|+\rangle\langle+| + \frac{1}{2}|-\rangle\langle-| \quad (1010)$$

$$= \frac{\mathbb{I}}{2}, \quad (1011)$$

$$A_3(\eta) = -\frac{1}{2}|-\rangle\langle+| \quad (1012)$$

$$= \frac{1}{4}(\sigma_z + i\sigma_y), \quad (1013)$$

$$A_3(-\eta) = -\frac{1}{2}|+\rangle\langle-| \quad (1014)$$

$$= \frac{1}{4}(\sigma_z - i\sigma_y). \quad (1015)$$

Neglecting the term proportional to the identity in the Hamiltonian we obtain that:

$$\frac{d\rho_S(t)}{dt} = -i\frac{\tilde{\Omega}}{2}[\sigma_x, \rho_S(t)] - K_{33}(\tilde{\Omega}, t) \left[ \frac{\sigma_z}{2}, \frac{1}{4}(\sigma_z + i\sigma_y)\rho_S(t) \right] - K_{33}(-\tilde{\Omega}, t) \left[ \frac{\sigma_z}{2}, \frac{1}{4}(\sigma_z - i\sigma_y)\rho_S(t) \right] \quad (1016)$$

$$- K_{33}^*(\tilde{\Omega}, t) \left[ \rho_S(t) \frac{1}{4}(\sigma_z + i\sigma_y), \frac{\sigma_z}{2} \right] - K_{33}^*(-\tilde{\Omega}, t) \left[ \rho_S(t) \frac{1}{4}(\sigma_z - i\sigma_y), \frac{\sigma_z}{2} \right]. \quad (1017)$$

Calculating the response functions extending the upper limit of  $\tau$  to  $\infty$ , we obtain:

$$K_{33}(\tilde{\Omega}) = \int_0^\infty \int_0^\infty J(\omega) G_+(\tau) e^{i\tilde{\Omega}\tau} d\tau d\omega \quad (1018)$$

$$= \int_0^\infty \int_0^\infty J(\omega) e^{i\tilde{\Omega}\tau} ((n(\omega) + 1)e^{-i\tau\omega} + n(\omega)e^{i\tau\omega}) d\tau d\omega \quad (1019)$$

$$= \int_0^\infty \int_0^\infty J(\omega) e^{i\tilde{\Omega}\tau} (n(\omega) + 1)e^{-i\tau\omega} d\tau d\omega \quad (1020)$$

$$= \int_0^\infty \int_0^\infty J(\omega) (n(\omega) + 1) e^{i\tilde{\Omega}\tau - i\tau\omega} d\tau d\omega \quad (1021)$$

$$= \int_0^\infty J(\omega) (n(\omega) + 1) \pi \delta(\tilde{\Omega} - \omega) d\omega \quad (1022)$$

$$= \pi J(\tilde{\Omega}) (n(\tilde{\Omega}) + 1), \quad (1023)$$

$$K_{33}(-\tilde{\Omega}) = \int_0^\infty \int_0^\infty J(\omega) G_+(\tau) e^{-i\tilde{\Omega}\tau} d\tau d\omega \quad (1024)$$

$$= \int_0^\infty \int_0^\infty J(\omega) e^{-i\tilde{\Omega}\tau} ((n(\omega) + 1)e^{-i\tau\omega} + n(\omega)e^{i\tau\omega}) d\tau d\omega \quad (1025)$$

$$= \int_0^\infty \int_0^\infty J(\omega) e^{-i\tilde{\Omega}\tau} n(\omega) e^{i\tau\omega} d\tau d\omega \quad (1026)$$

$$= \int_0^\infty \int_0^\infty J(\omega) n(\omega) e^{-i\tilde{\Omega}\tau + i\tau\omega} d\tau d\omega \quad (1027)$$

$$= \int_0^\infty J(\omega) n(\omega) \pi \delta(-\tilde{\Omega} + \omega) d\omega \quad (1028)$$

$$= \pi J(\tilde{\Omega}) n(\tilde{\Omega}). \quad (1029)$$

Here we have used  $\int_0^\infty ds e^{\pm i\epsilon s} = \pi \delta(\epsilon) \pm i \frac{\text{V.P.}}{\epsilon}$ , where V.P. denotes the Cauchy's principal value. Theses principal values are ignored because they lead to small renormalizations of the Hamiltonian. Furthermore we don't take

account of value associated to the matrix  $A_3(0)$  because the spectral density  $J(\omega)$  is equal to zero when  $\omega = 0$ . Replacing in the equation (1016) lead us to obtain:

$$\frac{d\rho_S(t)}{dt} = -i\frac{\tilde{\Omega}}{2} [\sigma_x, \rho_S(t)] - \frac{\pi}{8} J(\tilde{\Omega}) \left( (n(\tilde{\Omega}) + 1) [\sigma_z, (\sigma_z + i\sigma_y) \rho_S(t)] + n(\tilde{\Omega}) [\sigma_z, (\sigma_z - i\sigma_y) \rho_S(t)] \right) \quad (1030)$$

$$- \frac{\pi}{8} J(\tilde{\Omega}) \left( (n(\tilde{\Omega}) + 1) [\rho_S(t) (\sigma_z + i\sigma_y), \sigma_z] + n(\tilde{\Omega}) [\rho_S(t) (\sigma_z - i\sigma_y), \sigma_z] \right). \quad (1031)$$

This is the same result than the equation (S17), so we have proved that our general master equation allows to reproduce the results of the weak-coupling time-dependent. Now the master equation in the evolution time is given by

$$\frac{d\rho_S(t)}{dt} = -i\frac{\Omega(t)}{2} [\sigma_x, \rho_S(t)] - \frac{\pi}{8} J(\Omega(t)) \left( (n(\Omega(t)) + 1) [\sigma_z, (\sigma_z + i\sigma_y) \rho_S(t)] + n(\Omega(t)) [\sigma_z, (\sigma_z - i\sigma_y) \rho_S(t)] \right) \quad (1032)$$

$$- \frac{\pi}{8} J(\Omega(t)) \left( (n(\Omega(t)) + 1) [\rho_S(t) (\sigma_z + i\sigma_y), \sigma_z] + n(\Omega(t)) [\rho_S(t) (\sigma_z - i\sigma_y), \sigma_z] \right). \quad (1033)$$

## VI. TIME-DEPENDENT MULTI-SITE MODEL WITH V BATHS COUPLING

Let's consider the following Hamiltonian for a system of m-level system coupled to v-baths. We start with a time-dependent Hamiltonian of the form:

$$H(t) = H_S(t) + H_I + H_B, \quad (1034)$$

$$H_S(t) = \sum_n \varepsilon_n(t) |n\rangle\langle n| + \sum_{n \neq m} V_{nm}(t) |n\rangle\langle m|, \quad (1035)$$

$$H_I = \sum_{nuk} |n\rangle\langle n| \left( g_{nuk} b_{uk}^\dagger + g_{nuk}^* b_{uk} \right), \quad (1036)$$

$$H_B = \sum_{uk} \omega_{uk} b_{uk}^\dagger b_{uk}. \quad (1037)$$

### A. Variational Transformation

We consider the following operator:

$$V = \sum_{nuk} |n\rangle\langle n| \omega_{uk}^{-1} \left( f_{nuk} b_{uk}^\dagger - f_{nuk}^* b_{uk} \right) \quad (1038)$$

At first let's obtain  $e^{\pm V}$  under the transformation (1038), consider  $\hat{\varphi}_n = \sum_{uk} \omega_{uk}^{-1} \left( f_{nuk} b_{uk}^\dagger - f_{nuk}^* b_{uk} \right)$ , so the equation (1038) can be written as  $V = \sum_n |n\rangle\langle n| \hat{\varphi}_n$ , then we have:

$$e^{\pm V} = e^{\pm \sum_n |n\rangle\langle n| \hat{\varphi}_n} \quad (1039)$$

$$= \mathbb{I} \pm \sum_n |n\rangle\langle n| \hat{\varphi}_n + \frac{(\sum_n |n\rangle\langle n| \hat{\varphi}_n)^2}{2!} + \dots \quad (1040)$$

$$= \mathbb{I} \pm \sum_n |n\rangle\langle n| \hat{\varphi}_n + \frac{\sum_n |n\rangle\langle n| \hat{\varphi}_n^2}{2!} + \dots \quad (1041)$$

$$= \sum_n |n\rangle\langle n| \pm \sum_n |n\rangle\langle n| \hat{\varphi}_n + \frac{\sum_n |n\rangle\langle n| \hat{\varphi}_n^2}{2!} + \dots \quad (1042)$$

$$= \sum_n |n\rangle\langle n| \left( \mathbb{I} \pm \hat{\varphi}_n + \frac{\hat{\varphi}_n^2}{2!} + \dots \right) \quad (1043)$$

$$= \sum_n |n\rangle\langle n| e^{\pm \hat{\varphi}_n} \quad (1044)$$

Given that  $\left[ f_{nu\mathbf{k}} b_{u\mathbf{k}}^\dagger - f_{nu\mathbf{k}}^* b_{u\mathbf{k}}, f_{nu'\mathbf{k}'} b_{u'\mathbf{k}'}^\dagger - f_{nu'\mathbf{k}'}^* b_{u'\mathbf{k}'} \right] = 0$  for all  $\mathbf{k}', \mathbf{k}$  and  $u, u'$  then we can proof using the Zassenhaus formula and defining  $D(\pm \alpha_{nu\mathbf{k}}) = e^{\pm (\alpha_{nu\mathbf{k}} b_{u\mathbf{k}}^\dagger - \alpha_{nu\mathbf{k}}^* b_{u\mathbf{k}})}$  in the same way than (23) with  $\alpha_{nu\mathbf{k}} = \frac{f_{nu\mathbf{k}}}{\omega_{u\mathbf{k}}}$ :

$$e^{\pm \sum_{u\mathbf{k}} \omega_{u\mathbf{k}}^{-1} (f_{nu\mathbf{k}} b_{u\mathbf{k}}^\dagger - f_{nu\mathbf{k}}^* b_{u\mathbf{k}})} = \prod_u e^{\pm \sum_{\mathbf{k}} \omega_{u\mathbf{k}}^{-1} (f_{nu\mathbf{k}} b_{u\mathbf{k}}^\dagger - f_{nu\mathbf{k}}^* b_{u\mathbf{k}})} \quad (1045)$$

$$= \prod_u \left( \prod_{\mathbf{k}} e^{\pm \omega_{u\mathbf{k}}^{-1} (f_{nu\mathbf{k}} b_{u\mathbf{k}}^\dagger - f_{nu\mathbf{k}}^* b_{u\mathbf{k}})} \right) \quad (1046)$$

$$= \prod_u \left( \prod_{\mathbf{k}} D(\pm \alpha_{nu\mathbf{k}}) \right) \quad (1047)$$

$$= \prod_{u\mathbf{k}} D(\pm \alpha_{nu\mathbf{k}}) \quad (1048)$$

$$= \prod_u B_{nu\pm} \quad (1049)$$

$$B_{nu\pm} \equiv \prod_{\mathbf{k}} D(\pm \alpha_{nu\mathbf{k}}) \quad (1050)$$

As we can see  $e^{-V} = \sum_n |n\rangle\langle n| \prod_u B_{nu-}$  and  $e^V = \sum_n |n\rangle\langle n| \prod_u B_{nu+}$  this implies that  $e^{-V} e^V = \mathbb{I}$ . This allows us to write the canonical transformation in the following explicit way:

$$e^V A e^{-V} = \left( \sum_n |n\rangle\langle n| \prod_u B_{nu+} \right) A \left( \sum_n |n\rangle\langle n| \prod_u B_{nu-} \right) \quad (1051)$$

Now let's obtain the canonical transformation of the principal elements of the Hamiltonian (1034):

$$\overline{|0\rangle\langle 0|} = \left( \sum_n |n\rangle\langle n| \prod_u B_{nu+} \right) |0\rangle\langle 0| \left( \sum_n |n\rangle\langle n| \prod_u B_{nu-} \right), \quad (1052)$$

$$= \prod_u B_{0u+} |0\rangle\langle 0| \prod_u B_{0u-}, \quad (1053)$$

$$= |0\rangle\langle 0| \prod_u B_{0u+} \prod_u B_{0u-}, \quad (1054)$$

$$= |0\rangle\langle 0| \prod_u B_{0u+} B_{0u-} \quad (1055)$$

$$= |0\rangle\langle 0| \prod_u \mathbb{I} \quad (1056)$$

$$= |0\rangle\langle 0|. \quad (1057)$$

$$\overline{|m\rangle\langle n|} = \left( \sum_n |n\rangle\langle n| \prod_u B_{nu+} \right) |m\rangle\langle n| \left( \sum_n |n\rangle\langle n| \prod_u B_{nu-} \right), \quad (1058)$$

$$= |m\rangle\langle m| \prod_u B_{mu+} |m\rangle\langle n| \prod_u B_{nu-}, \quad (1059)$$

$$= |m\rangle\langle n| \prod_u B_{mu+} \prod_u B_{nu-}, \quad (1060)$$

$$= |m\rangle\langle n| \prod_u (B_{mu+} B_{nu-}), \quad m \neq n, \quad (1061)$$

$$= |m\rangle\langle n| \prod_u \left( \prod_{\mathbf{k}} D(\alpha_{muk}) \prod_{\mathbf{k}} D(-\alpha_{nuk}) \right), \quad (1062)$$

$$= |m\rangle\langle n| \prod_u \prod_{\mathbf{k}} (D(\alpha_{muk}) D(-\alpha_{nuk})), \quad (1063)$$

$$= |m\rangle\langle n| \prod_{u\mathbf{k}} \left( D(\alpha_{muk} - \alpha_{nuk}) \exp \left( \frac{1}{2} (-\alpha_{muk} \alpha_{nuk}^* + \alpha_{muk}^* \alpha_{nuk}) \right) \right). \quad (1064)$$

$$\Pi_u(B_{mu+} B_{nu-}) = \prod_{u\mathbf{k}} \left( D(\alpha_{muk} - \alpha_{nuk}) \exp \left( \frac{1}{2} (-\alpha_{muk} \alpha_{nuk}^* + \alpha_{muk}^* \alpha_{nuk}) \right) \right). \quad (1065)$$

$$\overline{\sum_{u\mathbf{k}} \omega_{u\mathbf{k}} b_{u\mathbf{k}}^\dagger b_{u\mathbf{k}}} = (\sum_n |n\rangle\langle n| \prod_u B_{nu+}) \sum_{u\mathbf{k}} \omega_{u\mathbf{k}} b_{u\mathbf{k}}^\dagger b_{u\mathbf{k}} (\sum_n |n\rangle\langle n| \prod_u B_{nu-}), \quad (1066)$$

$$= (|0\rangle\langle 0| \prod_u B_{0u+} + |1\rangle\langle 1| \prod_u B_{1u+} + \dots) (\sum_n |n\rangle\langle n| \sum_{u\mathbf{k}} \omega_{u\mathbf{k}} b_{u\mathbf{k}}^\dagger b_{u\mathbf{k}}) (|0\rangle\langle 0| \prod_u B_{0u-} + |1\rangle\langle 1| \prod_u B_{1u-} + \dots), \quad (1067)$$

$$= |0\rangle\langle 0| \prod_u B_{0u+} + \sum_{u\mathbf{k}} \omega_{u\mathbf{k}} b_{u\mathbf{k}}^\dagger b_{u\mathbf{k}} \prod_u B_{0u-} + |1\rangle\langle 1| \prod_u B_{1u+} + \sum_{u\mathbf{k}} \omega_{u\mathbf{k}} b_{u\mathbf{k}}^\dagger b_{u\mathbf{k}} \prod_u B_{1u-} + \dots, \quad (1068)$$

$$= |0\rangle\langle 0| \prod_u B_{0u+} + (\sum_{\mathbf{k}} \omega_{0\mathbf{k}} b_{0\mathbf{k}}^\dagger b_{0\mathbf{k}} + \sum_{\mathbf{k}} \omega_{1\mathbf{k}} b_{1\mathbf{k}}^\dagger b_{1\mathbf{k}} + \dots) \prod_u B_{0u-} + |1\rangle\langle 1| \prod_u B_{1u+} + (\sum_{\mathbf{k}} \omega_{0\mathbf{k}} b_{0\mathbf{k}}^\dagger b_{0\mathbf{k}} + \sum_{\mathbf{k}} \omega_{1\mathbf{k}} b_{1\mathbf{k}}^\dagger b_{1\mathbf{k}} + \dots) \prod_u B_{1u-} + \dots \quad (1069)$$

$$= |0\rangle\langle 0| (\prod_u B_{0u+} + \sum_{\mathbf{k}} \omega_{0\mathbf{k}} b_{0\mathbf{k}}^\dagger b_{0\mathbf{k}} \prod_u B_{0u-} + \prod_u B_{0u+} + \sum_{\mathbf{k}} \omega_{1\mathbf{k}} b_{1\mathbf{k}}^\dagger b_{1\mathbf{k}} \prod_u B_{0u-} + \dots) \quad (1070)$$

$$+ |1\rangle\langle 1| (\prod_u B_{1u+} + \sum_{\mathbf{k}} \omega_{0\mathbf{k}} b_{0\mathbf{k}}^\dagger b_{0\mathbf{k}} \prod_u B_{1u-} + \prod_u B_{1u+} + \sum_{\mathbf{k}} \omega_{1\mathbf{k}} b_{1\mathbf{k}}^\dagger b_{1\mathbf{k}} \prod_u B_{1u-} + \dots) + \dots \quad (1071)$$

$$= |0\rangle\langle 0| \left( \sum_{\mathbf{k}} \omega_{0\mathbf{k}} \left( b_{0\mathbf{k}}^\dagger - \frac{v_{00\mathbf{k}}}{\omega_{0\mathbf{k}}} \right) \left( b_{0\mathbf{k}} - \frac{v_{00\mathbf{k}}}{\omega_{0\mathbf{k}}} \right) + \sum_{\mathbf{k}} \omega_{1\mathbf{k}} \left( b_{1\mathbf{k}}^\dagger - \frac{v_{01\mathbf{k}}}{\omega_{1\mathbf{k}}} \right) \left( b_{0\mathbf{k}} - \frac{v_{01\mathbf{k}}}{\omega_{1\mathbf{k}}} \right) + \dots \right) \quad (1072)$$

$$+ |1\rangle\langle 1| \left( \sum_{\mathbf{k}} \omega_{0\mathbf{k}} \left( b_{0\mathbf{k}}^\dagger - \frac{v_{10\mathbf{k}}}{\omega_{0\mathbf{k}}} \right) \left( b_{0\mathbf{k}} - \frac{v_{10\mathbf{k}}}{\omega_{0\mathbf{k}}} \right) + \sum_{\mathbf{k}} \omega_{1\mathbf{k}} \left( b_{1\mathbf{k}}^\dagger - \frac{v_{11\mathbf{k}}}{\omega_{1\mathbf{k}}} \right) \left( b_{0\mathbf{k}} - \frac{v_{11\mathbf{k}}}{\omega_{1\mathbf{k}}} \right) + \dots \right) + \dots \quad (1073)$$

$$= |0\rangle\langle 0| \left( \sum_{u\mathbf{k}} \omega_{u\mathbf{k}} \left( b_{u\mathbf{k}}^\dagger - \frac{v_{0u\mathbf{k}}}{\omega_{u\mathbf{k}}} \right) \left( b_{u\mathbf{k}} - \frac{v_{0u\mathbf{k}}}{\omega_{u\mathbf{k}}} \right) \right) + |1\rangle\langle 1| \left( \sum_{u\mathbf{k}} \omega_{u\mathbf{k}} \left( b_{u\mathbf{k}}^\dagger - \frac{v_{1u\mathbf{k}}}{\omega_{u\mathbf{k}}} \right) \left( b_{u\mathbf{k}} - \frac{v_{1u\mathbf{k}}}{\omega_{u\mathbf{k}}} \right) \right) + \dots \quad (1074)$$

$$= \sum_{n\mathbf{u}\mathbf{k}} |n\rangle\langle n| \left( \omega_{u\mathbf{k}} \left( b_{u\mathbf{k}}^\dagger - \frac{v_{nu\mathbf{k}}}{\omega_{u\mathbf{k}}} \right) \left( b_{u\mathbf{k}} - \frac{v_{nu\mathbf{k}}}{\omega_{u\mathbf{k}}} \right) \right) \quad (1075)$$

$$= \sum_{n\mathbf{u}\mathbf{k}} |n\rangle\langle n| \left( \omega_{u\mathbf{k}} \left( b_{u\mathbf{k}}^\dagger b_{u\mathbf{k}} - \frac{v_{nu\mathbf{k}}}{\omega_{u\mathbf{k}}} b_{u\mathbf{k}}^\dagger - \frac{v_{nu\mathbf{k}}^*}{\omega_{u\mathbf{k}}} b_{u\mathbf{k}} + \left| \frac{v_{nu\mathbf{k}}}{\omega_{u\mathbf{k}}} \right|^2 \right) \right) \quad (1076)$$

$$= \sum_{n\mathbf{u}\mathbf{k}} |n\rangle\langle n| \omega_{u\mathbf{k}} b_{u\mathbf{k}}^\dagger b_{u\mathbf{k}} + \sum_{n\mathbf{u}\mathbf{k}} |n\rangle\langle n| \left( \frac{|v_{nu\mathbf{k}}|^2}{\omega_{u\mathbf{k}}} - v_{nu\mathbf{k}} b_{u\mathbf{k}}^\dagger - v_{nu\mathbf{k}}^* b_{u\mathbf{k}} \right) \quad (1077)$$

$$= \sum_{u\mathbf{k}} \omega_{u\mathbf{k}} b_{u\mathbf{k}}^\dagger b_{u\mathbf{k}} + \sum_{n\mathbf{u}\mathbf{k}} |n\rangle\langle n| \left( \frac{|v_{nu\mathbf{k}}|^2}{\omega_{u\mathbf{k}}} - (v_{nu\mathbf{k}} b_{u\mathbf{k}}^\dagger + v_{nu\mathbf{k}}^* b_{u\mathbf{k}}) \right) \quad (1078)$$

The transformed Hamiltonians of the equations (1035) to (1037) written in terms of (1052) to (1076) are:

$$\overline{H_S(t)} = \overline{\sum_n \varepsilon_n(t) |n\rangle\langle n| + \sum_{n \neq m} V_{nm}(t) |n\rangle\langle m|} \quad (1079)$$

$$= \overline{\sum_n \varepsilon_n(t) |n\rangle\langle n|} + \overline{\sum_{n \neq m} V_{nm}(t) |n\rangle\langle m|} \quad (1080)$$

$$= \sum_n \varepsilon_n(t) |n\rangle\langle n| + \sum_{n \neq m} V_{nm}(t) |n\rangle\langle m| \prod_u (B_{mu+} B_{nu-}) \quad (1081)$$

$$\overline{H_I} = \left( \sum_n |n\rangle\langle n| \prod_u B_{nu+} \right) \left( \sum_{nuk} |n\rangle\langle n| (g_{nuk} b_{uk}^\dagger + g_{nuk}^* b_{uk}) \right) \left( \sum_n |n\rangle\langle n| \prod_u B_{nu-} \right) \quad (1082)$$

$$= \left( \sum_n |n\rangle\langle n| \prod_u B_{nu+} \right) \left( \sum_{uk} |0\rangle\langle 0| (g_{0uk} b_{uk}^\dagger + g_{0uk}^* b_{uk}) + \dots \right) \left( \sum_n |n\rangle\langle n| \prod_u B_{nu-} \right) \quad (1083)$$

$$= \prod_u B_{0u+} \sum_{uk} |0\rangle\langle 0| (g_{0uk} b_{uk}^\dagger + g_{0uk}^* b_{uk}) \prod_u B_{0u-} + \prod_u B_{1u+} \sum_{uk} |1\rangle\langle 1| (g_{1uk} b_{uk}^\dagger + g_{1uk}^* b_{uk}) \prod_u B_{1u-} + \dots \quad (1084)$$

$$= \sum_{uk} |0\rangle\langle 0| (g_{0uk} \prod_u B_{0u+} b_{uk}^\dagger \prod_u B_{0u-} + g_{0uk}^* \prod_u B_{0u+} b_{uk} \prod_u B_{0u-}) + \sum_{uk} |1\rangle\langle 1| (g_{1uk} \prod_u B_{1u+} b_{uk}^\dagger \prod_u B_{1u-} + g_{1uk}^* \prod_u B_{1u+} b_{uk} \prod_u B_{1u-}) + \dots \quad (1085)$$

$$= \sum_{uk} |0\rangle\langle 0| \left( g_{0uk} \left( b_{uk}^\dagger - \frac{v_{0uk}^*}{\omega_{uk}} \right) + g_{0uk}^* \left( b_{uk} - \frac{v_{0uk}}{\omega_{uk}} \right) \right) + \sum_{uk} |1\rangle\langle 1| \left( g_{1uk} \left( b_{uk}^\dagger - \frac{v_{1uk}^*}{\omega_{uk}} \right) + g_{1uk}^* \left( b_{uk} - \frac{v_{1uk}}{\omega_{uk}} \right) \right) + \dots \quad (1086)$$

$$= \sum_{nuk} |n\rangle\langle n| \left( g_{nuk} \left( b_{uk}^\dagger - \frac{v_{nuk}^*}{\omega_{uk}} \right) + g_{nuk}^* \left( b_{uk} - \frac{v_{nuk}}{\omega_{uk}} \right) \right) \quad (1087)$$

$$= \sum_{nuk} |n\rangle\langle n| \left( g_{nuk} b_{uk}^\dagger + g_{nuk}^* b_{uk} - \left( g_{nuk} \frac{v_{nuk}^*}{\omega_{uk}} + g_{nuk}^* \frac{v_{nuk}}{\omega_{uk}} \right) \right) \quad (1088)$$

$$\overline{H_B} = \sum_{uk} \omega_{uk} b_{uk}^\dagger b_{uk} + \sum_{nuk} |n\rangle\langle n| \left( \frac{|v_{nuk}|^2}{\omega_{uk}} - (v_{nuk} b_{uk}^\dagger + v_{nuk}^* b_{uk}) \right) \quad (1089)$$

Joining this terms allow us to write the transformed Hamiltonian as:

$$\overline{H} = \sum_n \varepsilon_n(t) |n\rangle\langle n| + \sum_{n \neq m} V_{nm}(t) |n\rangle\langle m| \prod_u (B_{mu+} B_{nu-}) + \sum_{uk} \omega_{uk} b_{uk}^\dagger b_{uk} + \sum_{nuk} |n\rangle\langle n| \left( \frac{|v_{nuk}|^2}{\omega_{uk}} - (v_{nuk} b_{uk}^\dagger + v_{nuk}^* b_{uk}) \right) \quad (1090)$$

$$+ \sum_{nuk} |n\rangle\langle n| \left( g_{nuk} b_{uk}^\dagger + g_{nuk}^* b_{uk} - \left( g_{nuk} \frac{v_{nuk}^*}{\omega_{uk}} + g_{nuk}^* \frac{v_{nuk}}{\omega_{uk}} \right) \right) \quad (1091)$$

Let's define the following functions:

$$R_n(t) = \sum_{uk} \left( \frac{|v_{nuk}|^2}{\omega_{uk}} - \left( g_{nuk} \frac{v_{nuk}^*}{\omega_{uk}} + g_{nuk}^* \frac{v_{nuk}}{\omega_{uk}} \right) \right) \quad (1092)$$

$$B_{z,n}(t) = \sum_{uk} \left( (g_{nuk} - v_{nuk}) b_{uk}^\dagger + (g_{nuk} - v_{nuk})^* b_{uk} \right) \quad (1093)$$

Using the previous functions we have that (1090) can be re-written in the following way:

$$\overline{H} = \sum_n \varepsilon_n(t) |n\rangle\langle n| + \sum_{n \neq m} V_{nm}(t) |n\rangle\langle m| \prod_u (B_{mu+} B_{nu-}) + \sum_{uk} \omega_{uk} b_{uk}^\dagger b_{uk} + \sum_n R_n(t) |n\rangle\langle n| + \sum_n B_{z,n}(t) |n\rangle\langle n| \quad (1094)$$

$$(1095)$$

Now in order to separate the elements of the hamiltonian (1095) let's follow the references of the equations (225) and (236) to separate the hamiltonian, before proceeding to do this we need to consider the term of the form:

$$\langle \Pi_u (B_{mu+} B_{nu-}) \rangle_{\overline{H_0}} = \langle \Pi_{u\mathbf{k}} (D(\alpha_{mu\mathbf{k}} - \alpha_{nu\mathbf{k}}) \exp(\frac{1}{2}(-\alpha_{mu\mathbf{k}} \alpha_{nu\mathbf{k}}^* + \alpha_{mu\mathbf{k}}^* \alpha_{nu\mathbf{k}})) \rangle_{\overline{H_0}} \quad (1096)$$

$$= (\Pi_{u\mathbf{k}} \exp(\frac{1}{2}(-\alpha_{mu\mathbf{k}} \alpha_{nu\mathbf{k}}^* + \alpha_{mu\mathbf{k}}^* \alpha_{nu\mathbf{k}}))) \langle \Pi_{u\mathbf{k}} D(\alpha_{mu\mathbf{k}} - \alpha_{nu\mathbf{k}}) \rangle_{\overline{H_0}} \quad (1097)$$

$$= \left( \Pi_{u\mathbf{k}} \exp\left(\frac{(v_{mu\mathbf{k}}^* v_{nu\mathbf{k}} - v_{nu\mathbf{k}} v_{mu\mathbf{k}}^*)}{2\omega_{u\mathbf{k}}^2}\right) \right) \Pi_u \exp\left(-\frac{1}{2} \sum_{\mathbf{k}} \frac{|v_{mu\mathbf{k}} - v_{nu\mathbf{k}}|^2}{\omega_{u\mathbf{k}}^2} \coth\left(\frac{\beta\omega_{u\mathbf{k}}}{2}\right)\right) \quad (1098)$$

$$\equiv B_{nm} \quad (1099)$$

$$\langle \Pi_u (B_{nu+} B_{mu-}) \rangle_{\overline{H_0}} = \left( \Pi_{u\mathbf{k}} \exp\left(\frac{(v_{nu\mathbf{k}}^* v_{mu\mathbf{k}} - v_{mu\mathbf{k}} v_{nu\mathbf{k}}^*)}{2\omega_{u\mathbf{k}}^2}\right) \right) \Pi_u \exp\left(-\frac{1}{2} \sum_{\mathbf{k}} \frac{|v_{mu\mathbf{k}} - v_{nu\mathbf{k}}|^2}{\omega_{u\mathbf{k}}^2} \coth\left(\frac{\beta\omega_{u\mathbf{k}}}{2}\right)\right) \quad (1100)$$

$$= B_{nm}^* \quad (1101)$$

Following the reference [4] we define:

$$J_{nm} = \prod_u (B_{mu+} B_{nu-}) - B_{nm} \quad (1102)$$

As we can see:

$$J_{nm}^\dagger = \left( \prod_u (B_{mu+} B_{nu-}) - B_{nm} \right)^\dagger \quad (1103)$$

$$= \prod_u (B_{nu+} B_{mu-}) - B_{nm}^* \quad (1104)$$

$$= \prod_u (B_{nu+} B_{mu-}) - B_{mn} \quad (1105)$$

$$= J_{mn} \quad (1106)$$

We can separate the Hamiltonian (1095) on the following way using similar arguments to the precedent sections to obtain:

$$\overline{H_{\bar{S}}}(t) = \sum_n (\varepsilon_n(t) + R_n) |n\rangle\langle n| + \sum_{n \neq m} V_{nm}(t) |n\rangle\langle m| B_{nm} \quad (1107)$$

$$\overline{H_{\bar{I}}}(t) = \sum_{n \neq m} V_{nm}(t) |n\rangle\langle m| J_{nm} + \sum_n B_{z,n}(t) |n\rangle\langle n|, \quad (1108)$$

$$\overline{H_{\bar{B}}}(t) = \sum_{u\mathbf{k}} \omega_{u\mathbf{k}} b_{u\mathbf{k}}^\dagger b_{u\mathbf{k}} \quad (1109)$$

## B. Free-energy minimization

As first approach let's consider the minimization of the free-energy through the Feynman-Bogoliubov inequality

$$A \leq A_B \equiv -\frac{1}{\beta} \ln \left( \text{Tr} \left( e^{-\beta(\overline{H_{\bar{S}}}(t) + \overline{H_{\bar{B}}})} \right) \right) + \langle \overline{H_{\bar{I}}} \rangle_{\overline{H_{\bar{S}}}(t) + \overline{H_{\bar{B}}}} + O \left( \left\langle \overline{H_{\bar{I}}}^2 \right\rangle_{\overline{H_{\bar{S}}}(t) + \overline{H_{\bar{B}}}} \right). \quad (1110)$$

Taking the equations (246)-(254) and given that  $\text{Tr} \left( e^{-\beta \overline{H_{\bar{S}}}(t)} \right) = C(R_0, R_1, \dots, R_{d-1}, B_{01}, \dots, B_{0(d-1)}, \dots, B_{(d-2)(d-1)})$ , where each  $R_i$  and  $B_{kj}$  depend of the set of variational parameters  $\{v_{nu\mathbf{k}}\}$ . Given that the numbers  $v_{nu\mathbf{k}}$  are complex then we can separate them as  $v_{nu\mathbf{k}} = v_{nu\mathbf{k}}^{\Re} + i v_{nu\mathbf{k}}^{\Im}$ . So our approach will be based on the derivation respect to  $v_{nu\mathbf{k}}^{\Re}$  and  $v_{nu\mathbf{k}}^{\Im}$ . The Hamiltonian  $\overline{H_{\bar{S}}}(t)$  can be written like:

$$\overline{H_S(t)} = \sum_n \left( \varepsilon_n(t) + \sum_{\mathbf{uk}} \left( \frac{|v_{n\mathbf{uk}}|^2}{\omega_{\mathbf{uk}}} - \left( g_{n\mathbf{uk}} \frac{v_{n\mathbf{uk}}^*}{\omega_{\mathbf{uk}}} + g_{n\mathbf{uk}}^* \frac{v_{n\mathbf{uk}}}{\omega_{\mathbf{uk}}} \right) \right) \right) |n\rangle\langle n| \quad (1111)$$

$$+ \sum_{n \neq m} V_{nm}(t) |n\rangle\langle m| \left( \Pi_{\mathbf{uk}} \exp \left( \frac{(v_{m\mathbf{uk}}^* v_{n\mathbf{uk}} - v_{m\mathbf{uk}} v_{n\mathbf{uk}}^*)}{2\omega_{\mathbf{uk}}^2} \right) \right) \Pi_u \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \frac{|v_{m\mathbf{uk}} - v_{n\mathbf{uk}}|^2}{\omega_{\mathbf{uk}}^2} \coth \left( \frac{\beta_u \omega_{\mathbf{uk}}}{2} \right) \right) \quad (1112)$$

$$= \sum_n \left( \varepsilon_n(t) + \sum_{\mathbf{uk}} \left( \frac{|v_{n\mathbf{uk}}|^2}{\omega_{\mathbf{uk}}} - \frac{g_{n\mathbf{uk}} v_{n\mathbf{uk}}^* + g_{n\mathbf{uk}}^* v_{n\mathbf{uk}}}{\omega_{\mathbf{uk}}} \right) \right) |n\rangle\langle n| \quad (1113)$$

$$+ \sum_{n \neq m} V_{nm}(t) |n\rangle\langle m| \left( \Pi_{\mathbf{uk}} \exp \left( \frac{(v_{m\mathbf{uk}}^* v_{n\mathbf{uk}} - v_{m\mathbf{uk}} v_{n\mathbf{uk}}^*)}{2\omega_{\mathbf{uk}}^2} \right) \right) \Pi_u \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \frac{|v_{m\mathbf{uk}} - v_{n\mathbf{uk}}|^2}{\omega_{\mathbf{uk}}^2} \coth \left( \frac{\beta_u \omega_{\mathbf{uk}}}{2} \right) \right) \quad (1114)$$

$$= \sum_n \left( \varepsilon_n(t) + \sum_{\mathbf{uk}} \left( \frac{(v_{n\mathbf{uk}}^{\Re})^2 + (v_{n\mathbf{uk}}^{\Im})^2}{\omega_{\mathbf{uk}}} - \frac{(g_{n\mathbf{uk}} + g_{n\mathbf{uk}}^*) v_{n\mathbf{uk}}^{\Re} + i v_{n\mathbf{uk}}^{\Im} (g_{n\mathbf{uk}}^* - g_{n\mathbf{uk}})}{\omega_{\mathbf{uk}}} \right) \right) |n\rangle\langle n| \quad (1115)$$

$$+ \sum_{n \neq m} V_{nm}(t) |n\rangle\langle m| \left( \Pi_{\mathbf{uk}} \exp \left( \frac{(v_{m\mathbf{uk}}^* v_{n\mathbf{uk}} - v_{m\mathbf{uk}} v_{n\mathbf{uk}}^*)}{2\omega_{\mathbf{uk}}^2} \right) \right) \Pi_u \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \frac{|v_{m\mathbf{uk}} - v_{n\mathbf{uk}}|^2}{\omega_{\mathbf{uk}}^2} \coth \left( \frac{\beta_u \omega_{\mathbf{uk}}}{2} \right) \right) \quad (1116)$$

$$v_{m\mathbf{uk}}^* v_{n\mathbf{uk}} - v_{m\mathbf{uk}} v_{n\mathbf{uk}}^* = (v_{m\mathbf{uk}}^{\Re} - i v_{m\mathbf{uk}}^{\Im})(v_{n\mathbf{uk}}^{\Re} + i v_{n\mathbf{uk}}^{\Im}) - (v_{m\mathbf{uk}}^{\Re} + i v_{m\mathbf{uk}}^{\Im})(v_{n\mathbf{uk}}^{\Re} - i v_{n\mathbf{uk}}^{\Im}) \quad (1117)$$

$$= (v_{m\mathbf{uk}}^{\Re} v_{n\mathbf{uk}}^{\Re} + i v_{n\mathbf{uk}}^{\Im} v_{m\mathbf{uk}}^{\Re} - i v_{m\mathbf{uk}}^{\Im} v_{n\mathbf{uk}}^{\Re} + v_{m\mathbf{uk}}^{\Im} v_{n\mathbf{uk}}^{\Im}) \quad (1118)$$

$$- (v_{m\mathbf{uk}}^{\Re} v_{n\mathbf{uk}}^{\Re} - i v_{n\mathbf{uk}}^{\Im} v_{m\mathbf{uk}}^{\Re} + i v_{m\mathbf{uk}}^{\Im} v_{n\mathbf{uk}}^{\Re} + v_{m\mathbf{uk}}^{\Im} v_{n\mathbf{uk}}^{\Im}) \quad (1119)$$

$$= 2i (v_{n\mathbf{uk}}^{\Im} v_{m\mathbf{uk}}^{\Re} - v_{m\mathbf{uk}}^{\Im} v_{n\mathbf{uk}}^{\Re}) \quad (1120)$$

$$\overline{H_S(t)} = \sum_n \left( \varepsilon_n(t) + \sum_{\mathbf{uk}} \left( \frac{(v_{n\mathbf{uk}}^{\Re})^2 + (v_{n\mathbf{uk}}^{\Im})^2}{\omega_{\mathbf{uk}}} - \frac{(g_{n\mathbf{uk}} + g_{n\mathbf{uk}}^*) v_{n\mathbf{uk}}^{\Re} + i v_{n\mathbf{uk}}^{\Im} (g_{n\mathbf{uk}}^* - g_{n\mathbf{uk}})}{\omega_{\mathbf{uk}}} \right) \right) |n\rangle\langle n| \quad (1121)$$

$$+ \sum_{n \neq m} V_{nm}(t) |n\rangle\langle m| \left( \Pi_{\mathbf{uk}} \exp \left( \frac{i(v_{n\mathbf{uk}}^{\Im} v_{m\mathbf{uk}}^{\Re} - v_{m\mathbf{uk}}^{\Im} v_{n\mathbf{uk}}^{\Re})}{\omega_{\mathbf{uk}}^2} \right) \right) \Pi_u \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \frac{|v_{m\mathbf{uk}} - v_{n\mathbf{uk}}|^2}{\omega_{\mathbf{uk}}^2} \coth \left( \frac{\beta_u \omega_{\mathbf{uk}}}{2} \right) \right) \quad (1122)$$

$$|v_{m\mathbf{uk}} - v_{n\mathbf{uk}}|^2 = (v_{m\mathbf{uk}} - v_{n\mathbf{uk}})(v_{m\mathbf{uk}} - v_{n\mathbf{uk}})^* \quad (1123)$$

$$= |v_{m\mathbf{uk}}|^2 + |v_{n\mathbf{uk}}|^2 - (v_{n\mathbf{uk}} v_{m\mathbf{uk}}^* + v_{m\mathbf{uk}} v_{n\mathbf{uk}}^*) \quad (1124)$$

$$= (v_{m\mathbf{uk}}^{\Re})^2 + (v_{m\mathbf{uk}}^{\Im})^2 + (v_{n\mathbf{uk}}^{\Re})^2 + (v_{n\mathbf{uk}}^{\Im})^2 - (v_{n\mathbf{uk}}^{\Re} + i v_{n\mathbf{uk}}^{\Im})(v_{m\mathbf{uk}}^{\Re} - i v_{m\mathbf{uk}}^{\Im}) \quad (1125)$$

$$- (v_{n\mathbf{uk}}^{\Re} - i v_{n\mathbf{uk}}^{\Im})(v_{m\mathbf{uk}}^{\Re} + i v_{m\mathbf{uk}}^{\Im}) \quad (1126)$$

$$= (v_{m\mathbf{uk}}^{\Re})^2 + (v_{m\mathbf{uk}}^{\Im})^2 + (v_{n\mathbf{uk}}^{\Re})^2 + (v_{n\mathbf{uk}}^{\Im})^2 - 2(v_{n\mathbf{uk}}^{\Re} v_{m\mathbf{uk}}^{\Re} + v_{n\mathbf{uk}}^{\Im} v_{m\mathbf{uk}}^{\Im}) \quad (1127)$$

$$= (v_{m\mathbf{uk}}^{\Re} - v_{n\mathbf{uk}}^{\Re})^2 + (v_{m\mathbf{uk}}^{\Im} - v_{n\mathbf{uk}}^{\Im})^2 \quad (1128)$$

$$R_n(t) = \sum_{\mathbf{uk}} \left( \frac{|v_{n\mathbf{uk}}|^2}{\omega_{\mathbf{uk}}} - \left( g_{n\mathbf{uk}} \frac{v_{n\mathbf{uk}}^*}{\omega_{\mathbf{uk}}} + g_{n\mathbf{uk}}^* \frac{v_{n\mathbf{uk}}}{\omega_{\mathbf{uk}}} \right) \right) \quad (1129)$$

$$= \sum_{\mathbf{uk}} \left( \frac{(v_{n\mathbf{uk}}^{\Re})^2 + (v_{n\mathbf{uk}}^{\Im})^2 - (g_{n\mathbf{uk}} + g_{n\mathbf{uk}}^*) v_{n\mathbf{uk}}^{\Re} - i v_{n\mathbf{uk}}^{\Im} (g_{n\mathbf{uk}}^* - g_{n\mathbf{uk}})}{\omega_{\mathbf{uk}}} \right) \quad (1130)$$

$$= \sum_{\mathbf{uk}} \left( \frac{(v_{n\mathbf{uk}}^{\Re})^2 + (v_{n\mathbf{uk}}^{\Im})^2 - 2g_{n\mathbf{uk}}^{\Re} v_{n\mathbf{uk}}^{\Re} - 2g_{n\mathbf{uk}}^{\Im} v_{n\mathbf{uk}}^{\Im}}{\omega_{\mathbf{uk}}} \right) \quad (1131)$$

$$B_{mn} = \left( \Pi_{\mathbf{uk}} \exp \left( \frac{(v_{m\mathbf{uk}}^* v_{n\mathbf{uk}} - v_{m\mathbf{uk}} v_{n\mathbf{uk}}^*)}{2\omega_{\mathbf{uk}}^2} \right) \right) \Pi_u \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \frac{|v_{m\mathbf{uk}} - v_{n\mathbf{uk}}|^2}{\omega_{\mathbf{uk}}^2} \coth \left( \frac{\beta_u \omega_{\mathbf{uk}}}{2} \right) \right) \quad (1132)$$

$$= \left( \Pi_{\mathbf{uk}} \exp \left( \frac{i(v_{n\mathbf{uk}}^{\Im} v_{m\mathbf{uk}}^{\Re} - v_{m\mathbf{uk}}^{\Im} v_{n\mathbf{uk}}^{\Re})}{\omega_{\mathbf{uk}}^2} \right) \right) \Pi_u \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \frac{(v_{m\mathbf{uk}}^{\Re} - v_{n\mathbf{uk}}^{\Re})^2 + (v_{m\mathbf{uk}}^{\Im} - v_{n\mathbf{uk}}^{\Im})^2}{\omega_{\mathbf{uk}}^2} \coth \left( \frac{\beta_u \omega_{\mathbf{uk}}}{2} \right) \right) \quad (1133)$$



Then we can obtain using the chain rule that:

$$\frac{\partial R_{n'}}{\partial v_{nuk}^{\Re}} = \frac{\partial}{\partial v_{nuk}^{\Re}} \sum_{uk} \left( \frac{(v_{nuk}^{\Re})^2 + (v_{nuk}^{\Im})^2 - 2g_{nuk}^{\Re} v_{nuk}^{\Re} - 2g_{nuk}^{\Im} v_{nuk}^{\Im}}{\omega_{uk}} \right) \quad (1134)$$

$$= \frac{2v_{nuk}^{\Re} - 2g_{nuk}^{\Re}}{\omega_{uk}} \delta_{nn'} \quad (1135)$$

$$= 2 \frac{v_{nuk}^{\Re} - g_{nuk}^{\Re}}{\omega_{uk}} \delta_{nn'} \quad (1136)$$

$$\frac{\partial R_{n'}}{\partial v_{nuk}^{\Im}} = \frac{\partial}{\partial v_{nuk}^{\Im}} \sum_{uk} \left( \frac{(v_{nuk}^{\Re})^2 + (v_{nuk}^{\Im})^2 - 2g_{nuk}^{\Re} v_{nuk}^{\Re} - 2g_{nuk}^{\Im} v_{nuk}^{\Im}}{\omega_{uk}} \right) \quad (1137)$$

$$= \frac{2v_{nuk}^{\Im} - 2g_{nuk}^{\Im}}{\omega_{uk}} \delta_{nn'} \quad (1138)$$

$$= 2 \frac{v_{nuk}^{\Im} - g_{nuk}^{\Im}}{\omega_{uk}} \delta_{nn'} \quad (1139)$$

Given that:

$$\ln B_{mn} = \ln \left( \left( \prod_{uk} \exp \left( \frac{i(v_{nuk}^{\Im} v_{muk}^{\Re} - v_{muk}^{\Im} v_{nuk}^{\Re})}{\omega_{uk}^2} \right) \right) \prod_u \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \frac{(v_{muk}^{\Re} - v_{nuk}^{\Re})^2 + (v_{muk}^{\Im} - v_{nuk}^{\Im})^2}{\omega_{uk}^2} \coth \left( \frac{\beta_u \omega_{uk}}{2} \right) \right) \right) \quad (1140)$$

$$= \sum_{uk} \ln \exp \left( \frac{i(v_{nuk}^{\Im} v_{muk}^{\Re} - v_{muk}^{\Im} v_{nuk}^{\Re})}{\omega_{uk}^2} \right) + \sum_u \ln \exp \left( -\frac{1}{2} \sum_{\mathbf{k}} \frac{(v_{muk}^{\Re} - v_{nuk}^{\Re})^2 + (v_{muk}^{\Im} - v_{nuk}^{\Im})^2}{\omega_{uk}^2} \coth \left( \frac{\beta_u \omega_{uk}}{2} \right) \right) \quad (1141)$$

$$= \sum_{uk} \left( \frac{i(v_{nuk}^{\Im} v_{muk}^{\Re} - v_{muk}^{\Im} v_{nuk}^{\Re})}{\omega_{uk}^2} \right) + \sum_{uk} \left( -\frac{1}{2} \frac{(v_{muk}^{\Re} - v_{nuk}^{\Re})^2 + (v_{muk}^{\Im} - v_{nuk}^{\Im})^2}{\omega_{uk}^2} \coth \left( \frac{\beta_u \omega_{uk}}{2} \right) \right) \quad (1142)$$

$$\frac{\partial \ln B_{mn}}{\partial v_{nuk}^{\Re}} = \frac{-i v_{muk}^{\Im} - (v_{nuk}^{\Re} - v_{muk}^{\Re}) \coth \left( \frac{\beta_u \omega_{uk}}{2} \right)}{\omega_{uk}^2} \quad (1143)$$

$$\frac{\partial \ln B_{mn}}{\partial v_{nuk}^{\Im}} = \frac{i v_{muk}^{\Re} - (v_{nuk}^{\Im} - v_{muk}^{\Im}) \coth \left( \frac{\beta_u \omega_{uk}}{2} \right)}{\omega_{uk}^2} \quad (1144)$$

$$\frac{\partial \ln B_{mn}}{\partial a} = \frac{1}{B_{mn}} \frac{\partial B_{mn}}{\partial a} \quad (1145)$$

$$\frac{\partial B_{mn}}{\partial a} = B_{mn} \frac{\partial \ln B_{mn}}{\partial a} \quad (1146)$$

$$\frac{\partial B_{mn}}{\partial a} = \frac{\partial (B_{nm})^{\dagger}}{\partial a} \quad (1147)$$

Then the principal derivates are given by:

$$\frac{\partial B_{mn}}{\partial v_{n\mathbf{k}}^{\Re}} = B_{mn} \frac{\partial \ln B_{mn}}{\partial v_{n\mathbf{k}}^{\Re}} \quad (1148)$$

$$= B_{mn} \left( \frac{-iv_{m\mathbf{k}}^{\Im} - (v_{n\mathbf{k}}^{\Re} - v_{m\mathbf{k}}^{\Re}) \coth\left(\frac{\beta_u \omega_{u\mathbf{k}}}{2}\right)}{\omega_{u\mathbf{k}}^2} \right) \quad (1149)$$

$$= B_{mn} \left( \frac{-iv_{m\mathbf{k}}^{\Im} + (v_{m\mathbf{k}}^{\Re} - v_{n\mathbf{k}}^{\Re}) \coth\left(\frac{\beta_u \omega_{u\mathbf{k}}}{2}\right)}{\omega_{u\mathbf{k}}^2} \right) \quad (1150)$$

$$\frac{\partial B_{nm}}{\partial v_{n\mathbf{k}}^{\Re}} = \left( \frac{\partial B_{mn}}{\partial v_{n\mathbf{k}}^{\Re}} \right)^{\dagger} \quad (1151)$$

$$= \left( B_{mn} \left( \frac{-iv_{m\mathbf{k}}^{\Im} + (v_{m\mathbf{k}}^{\Re} - v_{n\mathbf{k}}^{\Re}) \coth\left(\frac{\beta_u \omega_{u\mathbf{k}}}{2}\right)}{\omega_{u\mathbf{k}}^2} \right) \right)^{\dagger} \quad (1152)$$

$$= B_{nm} \left( \frac{iv_{m\mathbf{k}}^{\Im} + (v_{m\mathbf{k}}^{\Re} - v_{n\mathbf{k}}^{\Re}) \coth\left(\frac{\beta_u \omega_{u\mathbf{k}}}{2}\right)}{\omega_{u\mathbf{k}}^2} \right) \quad (1153)$$

$$\frac{\partial B_{mn}}{\partial v_{n\mathbf{k}}^{\Im}} = B_{mn} \frac{\partial \ln B_{mn}}{\partial v_{n\mathbf{k}}^{\Im}} \quad (1154)$$

$$= B_{mn} \left( \frac{iv_{m\mathbf{k}}^{\Re} - (v_{n\mathbf{k}}^{\Im} - v_{m\mathbf{k}}^{\Im}) \coth\left(\frac{\beta_u \omega_{u\mathbf{k}}}{2}\right)}{\omega_{u\mathbf{k}}^2} \right) \quad (1155)$$

$$= B_{mn} \left( \frac{iv_{m\mathbf{k}}^{\Re} + (v_{m\mathbf{k}}^{\Im} - v_{n\mathbf{k}}^{\Im}) \coth\left(\frac{\beta_u \omega_{u\mathbf{k}}}{2}\right)}{\omega_{u\mathbf{k}}^2} \right) \quad (1156)$$

$$\frac{\partial B_{nm}}{\partial v_{n\mathbf{k}}^{\Im}} = \left( \frac{\partial B_{mn}}{\partial v_{n\mathbf{k}}^{\Im}} \right)^{\dagger} \quad (1157)$$

$$= (B_{mn})^{\dagger} \quad (1158)$$

$$= B_{nm} \left( \frac{-iv_{m\mathbf{k}}^{\Re} + (v_{m\mathbf{k}}^{\Im} - v_{n\mathbf{k}}^{\Im}) \coth\left(\frac{\beta_u \omega_{u\mathbf{k}}}{2}\right)}{\omega_{u\mathbf{k}}^2} \right) \quad (1159)$$

Introducing this derivatives in the equation (1134) give us:

$$\frac{\partial A_{\mathbf{B}}}{\partial v_{n\mathbf{k}}^{\Re}} = \frac{\partial A_{\mathbf{B}}}{\partial R_n} \left( 2 \frac{v_{n\mathbf{k}}^{\Re} - g_{u\mathbf{k}}^{\Re}}{\omega_{u\mathbf{k}}} \right) + \sum_{n < m} \left( \frac{\partial A_{\mathbf{B}}}{\partial B_{nm}} B_{nm} \left( \frac{iv_{m\mathbf{k}}^{\Im} + (v_{m\mathbf{k}}^{\Re} - v_{n\mathbf{k}}^{\Re}) \coth\left(\frac{\beta_u \omega_{u\mathbf{k}}}{2}\right)}{\omega_{u\mathbf{k}}^2} \right) \right) \quad (1160)$$

$$+ \frac{\partial A_{\mathbf{B}}}{\partial B_{mn}} B_{mn} \left( \frac{-iv_{m\mathbf{k}}^{\Im} + (v_{m\mathbf{k}}^{\Re} - v_{n\mathbf{k}}^{\Re}) \coth\left(\frac{\beta_u \omega_{u\mathbf{k}}}{2}\right)}{\omega_{u\mathbf{k}}^2} \right) \quad (1161)$$

$$= 0 \quad (1162)$$

We can obtain the variational parameters:

$$-2 \frac{\partial A_B}{\partial R_n} \frac{v_{nuk}^{\Re}}{\omega_{uk}} + \sum_{n < m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \frac{v_{nuk}^{\Re} \coth\left(\frac{\beta_u \omega_{uk}}{2}\right)}{\omega_{uk}^2} + \frac{\partial A_B}{\partial B_{mn}} B_{mn} \frac{v_{nuk}^{\Re} \coth\left(\frac{\beta_u \omega_{uk}}{2}\right)}{\omega_{uk}^2} \right) \quad (1163)$$

$$= -\frac{\partial A_B}{\partial R_n} \frac{2g_{nuk}^{\Re}}{\omega_{uk}} + \sum_{n < m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \left( \frac{iv_{muk}^{\Im} + v_{muk}^{\Re} \coth\left(\frac{\beta_u \omega_{uk}}{2}\right)}{\omega_{uk}^2} \right) + \frac{\partial A_B}{\partial B_{mn}} B_{mn} \left( \frac{-iv_{muk}^{\Im} + v_{muk}^{\Re} \coth\left(\frac{\beta_u \omega_{uk}}{2}\right)}{\omega_{uk}^2} \right) \right) \quad (1164)$$

$$v_{nuk}^{\Re} = \frac{\frac{\partial A_B}{\partial R_n} \frac{2g_{nuk}^{\Re}}{\omega_{uk}} - \sum_{n < m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \left( \frac{iv_{muk}^{\Im} + v_{muk}^{\Re} \coth\left(\frac{\beta_u \omega_{uk}}{2}\right)}{\omega_{uk}^2} \right) + \frac{\partial A_B}{\partial B_{mn}} B_{mn} \left( \frac{-iv_{muk}^{\Im} + v_{muk}^{\Re} \coth\left(\frac{\beta_u \omega_{uk}}{2}\right)}{\omega_{uk}^2} \right) \right)}{2 \frac{\partial A_B}{\partial R_n} \frac{1}{\omega_{uk}} - \sum_{n \neq m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \frac{\coth\left(\frac{\beta_u \omega_{uk}}{2}\right)}{\omega_{uk}^2} + \frac{\partial A_B}{\partial B_{mn}} B_{mn} \frac{\coth\left(\frac{\beta_u \omega_{uk}}{2}\right)}{\omega_{uk}^2} \right)} \quad (1165)$$

$$= \frac{2g_{nuk}^{\Re} \omega_{uk} \frac{\partial A_B}{\partial R_n} - \sum_{n < m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} (iv_{muk}^{\Im} + v_{muk}^{\Re} \coth\left(\frac{\beta_u \omega_{uk}}{2}\right)) + \frac{\partial A_B}{\partial B_{mn}} B_{mn} (-iv_{muk}^{\Im} + v_{muk}^{\Re} \coth\left(\frac{\beta_u \omega_{uk}}{2}\right)) \right)}{2\omega_{uk} \frac{\partial A_B}{\partial R_n} - \sum_{n \neq m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \coth\left(\frac{\beta_u \omega_{uk}}{2}\right) + \frac{\partial A_B}{\partial B_{mn}} B_{mn} \coth\left(\frac{\beta_u \omega_{uk}}{2}\right) \right)} \quad (1166)$$

Let's consider the imaginary part of the variation parameters

$$\frac{\partial A_B}{\partial v_{nuk}^{\Im}} = \frac{\partial A_B}{\partial R_n} \left( 2 \frac{v_{nuk}^{\Im} - g_{nuk}^{\Im}}{\omega_{uk}} \right) + \sum_{n < m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \left( \frac{-iv_{muk}^{\Re} - (v_{nuk}^{\Im} - v_{muk}^{\Im}) \coth\left(\frac{\beta_u \omega_{uk}}{2}\right)}{\omega_{uk}^2} \right) \right) \quad (1167)$$

$$+ \frac{\partial A_B}{\partial B_{mn}} B_{mn} \left( \frac{iv_{muk}^{\Re} - (v_{nuk}^{\Im} - v_{muk}^{\Im}) \coth\left(\frac{\beta_u \omega_{uk}}{2}\right)}{\omega_{uk}^2} \right) \quad (1168)$$

$$= 0 \quad (1169)$$

Rearranging we obtain

$$-2 \frac{\partial A_B}{\partial R_n} \frac{v_{n\mathbf{u}\mathbf{k}}^3}{\omega_{\mathbf{u}\mathbf{k}}} + \sum_{n < m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \frac{v_{n\mathbf{u}\mathbf{k}}^3 \coth\left(\frac{\beta_u \omega_{\mathbf{u}\mathbf{k}}}{2}\right)}{\omega_{\mathbf{u}\mathbf{k}}^2} + \frac{\partial A_B}{\partial B_{mn}} B_{mn} \frac{v_{n\mathbf{u}\mathbf{k}}^3 \coth\left(\frac{\beta_u \omega_{\mathbf{u}\mathbf{k}}}{2}\right)}{\omega_{\mathbf{u}\mathbf{k}}^2} \right) \quad (1170)$$

$$= -2 \frac{\partial A_B}{\partial R_n} \frac{g_{n\mathbf{u}\mathbf{k}}^{\mathfrak{I}}}{\omega_{\mathbf{u}\mathbf{k}}} + \sum_{n < m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \left( \frac{-iv_{m\mathbf{u}\mathbf{k}}^{\Re} + v_{m\mathbf{u}\mathbf{k}}^{\mathfrak{I}} \coth\left(\frac{\beta_{\mathbf{u}} \omega_{\mathbf{u}\mathbf{k}}}{2}\right)}{\omega_{\mathbf{u}\mathbf{k}}^2} \right) + \frac{\partial A_B}{\partial B_{mn}} B_{mn} \left( \frac{iv_{m\mathbf{u}\mathbf{k}}^{\Re} + v_{m\mathbf{u}\mathbf{k}}^{\mathfrak{I}} \coth\left(\frac{\beta_{\mathbf{u}} \omega_{\mathbf{u}\mathbf{k}}}{2}\right)}{\omega_{\mathbf{u}\mathbf{k}}^2} \right) \right) \quad (1171)$$

$$v_{nuk}^{\mathfrak{S}} = \frac{2 \frac{\partial A_B}{\partial R_n} \frac{g_{nuk}^{\mathfrak{S}}}{\omega_{uk}} - \sum_{n < m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \left( \frac{-iv_{muk}^{\mathfrak{R}} + v_{muk}^{\mathfrak{S}} \coth\left(\frac{\beta_{uuk}}{2}\right)}{\omega_{uk}^2} \right) + \frac{\partial A_B}{\partial B_{mn}} B_{mn} \left( \frac{iv_{muk}^{\mathfrak{R}} + v_{muk}^{\mathfrak{S}} \coth\left(\frac{\beta_{uuk}}{2}\right)}{\omega_{uk}^2} \right) \right)}{2 \frac{\partial A_B}{\partial R_n} \frac{1}{\omega_{uk}} - \sum_{n < m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \frac{\coth\left(\frac{\beta_{uuk}}{2}\right)}{\omega_{uk}^2} + \frac{\partial A_B}{\partial B_{mn}} B_{mn} \frac{\coth\left(\frac{\beta_{uuk}}{2}\right)}{\omega_{uk}^2} \right)} \quad (1172)$$

$$= \frac{2g_{nuk}^{\Im} \omega_{uk} \frac{\partial A_{\mathbb{B}}}{\partial R_n} - \sum_{n < m} \left( \frac{\partial A_{\mathbb{B}}}{\partial B_{nm}} B_{nm} \left( -iv_{muk}^{\Re} + v_{muk}^{\Im} \coth \left( \frac{\beta_u \omega_{uk}}{2} \right) \right) + \frac{\partial A_{\mathbb{B}}}{\partial B_{mn}} B_{mn} \left( iv_{muk}^{\Re} + v_{muk}^{\Im} \coth \left( \frac{\beta_u \omega_{uk}}{2} \right) \right) \right)}{2\omega_{uk} \frac{\partial A_{\mathbb{B}}}{\partial R_n} - \sum_{n < m} \left( \frac{\partial A_{\mathbb{B}}}{\partial B_{nm}} B_{nm} \coth \left( \frac{\beta_u \omega_{uk}}{2} \right) + \frac{\partial A_{\mathbb{B}}}{\partial B_{mn}} B_{mn} \coth \left( \frac{\beta_u \omega_{uk}}{2} \right) \right)} \quad (1173)$$

$$v_{n\mathbf{u}\mathbf{k}} = v_{n\mathbf{u}\mathbf{k}}^{\Re} + \mathrm{i}v_{n\mathbf{u}\mathbf{k}}^{\Im} \quad (1174)$$

$$= \frac{2g_{n\mathbf{u}\mathbf{k}}^{\Re}\omega_{\mathbf{u}\mathbf{k}}\frac{\partial A_{\mathbf{B}}}{\partial R_n} - \sum_{n < m} \left( \frac{\partial A_{\mathbf{B}}}{\partial B_{nm}} B_{nm} \left( i v_{m\mathbf{u}\mathbf{k}}^{\Im} + v_{m\mathbf{u}\mathbf{k}}^{\Re} \coth \left( \frac{\beta_{\mathbf{u}\mathbf{u}\mathbf{k}}}{2} \right) \right) + \frac{\partial A_{\mathbf{B}}}{\partial B_{mn}} B_{mn} \left( -i v_{m\mathbf{u}\mathbf{k}}^{\Im} + v_{m\mathbf{u}\mathbf{k}}^{\Re} \coth \left( \frac{\beta_{\mathbf{u}\mathbf{u}\mathbf{k}}}{2} \right) \right) \right)}{2\omega_{\mathbf{u}\mathbf{k}}\frac{\partial A_{\mathbf{B}}}{\partial R_n} - \sum_{n < m} \left( \frac{\partial A_{\mathbf{B}}}{\partial B_{nm}} B_{nm} \coth \left( \frac{\beta_{\mathbf{u}\mathbf{u}\mathbf{k}}}{2} \right) + \frac{\partial A_{\mathbf{B}}}{\partial B_{mn}} B_{mn} \coth \left( \frac{\beta_{\mathbf{u}\mathbf{u}\mathbf{k}}}{2} \right) \right)} \quad (1175)$$

$$\frac{2g_{nuk}^{\mathfrak{S}}\omega_{uk}\frac{\partial A_{\mathbf{B}}}{\partial R_n}-\sum_{n<m}\left(\frac{\partial A_{\mathbf{B}}}{\partial B_{nm}}B_{nm}\left(-iv_{muk}^{\mathfrak{R}}+v_{muk}^{\mathfrak{S}}\coth\left(\frac{\beta_u\omega_{uk}}{2}\right)\right)+\frac{\partial A_{\mathbf{B}}}{\partial B_{mn}}B_{mn}\left(iv_{muk}^{\mathfrak{R}}+v_{muk}^{\mathfrak{S}}\coth\left(\frac{\beta_u\omega_{uk}}{2}\right)\right)\right)}{2\omega_{uk}\frac{\partial A_{\mathbf{B}}}{\partial R_n}-\sum_{n<m}\left(\frac{\partial A_{\mathbf{B}}}{\partial B_{nm}}B_{nm}\coth\left(\frac{\beta_u\omega_{uk}}{2}\right)+\frac{\partial A_{\mathbf{B}}}{\partial B_{mn}}B_{mn}\coth\left(\frac{\beta_u\omega_{uk}}{2}\right)\right)} \quad (1176)$$

$$= \frac{2g_{\mathfrak{R}}^{\mathfrak{R}}\omega_{\mathfrak{u}\mathfrak{k}}\frac{\partial A_{\mathfrak{B}}}{\partial R_n} + 2ig_{\mathfrak{R}}^{\mathfrak{I}}\omega_{\mathfrak{u}\mathfrak{k}}\frac{\partial A_{\mathfrak{B}}}{\partial R_n}}{2\omega_{\mathfrak{u}\mathfrak{k}}\frac{\partial A_{\mathfrak{B}}}{\partial R_n} - \sum_{n < m} \left( \frac{\partial A_{\mathfrak{B}}}{\partial B_{nm}} B_{nm} \coth \left( \frac{\beta_{\mathfrak{u}}\omega_{\mathfrak{u}\mathfrak{k}}}{2} \right) + \frac{\partial A_{\mathfrak{B}}}{\partial B_{mn}} B_{mn} \coth \left( \frac{\beta_{\mathfrak{u}}\omega_{\mathfrak{u}\mathfrak{k}}}{2} \right) \right)} \quad (1177)$$

$$-\frac{\sum_{n < m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \left( i v_{m\mathbf{k}}^{\Im} + v_{m\mathbf{k}}^{\Re} \coth \left( \frac{\beta_u \omega_{u\mathbf{k}}}{2} \right) \right) + \frac{\partial A_B}{\partial B_{mn}} B_{mn} \left( -i v_{m\mathbf{k}}^{\Im} + v_{m\mathbf{k}}^{\Re} \coth \left( \frac{\beta_u \omega_{u\mathbf{k}}}{2} \right) \right) \right)}{2\omega_{u\mathbf{k}} \frac{\partial A_B}{\partial R_n} - \sum_{n < m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \coth \left( \frac{\beta_u \omega_{u\mathbf{k}}}{2} \right) + \frac{\partial A_B}{\partial B_{mn}} B_{mn} \coth \left( \frac{\beta_u \omega_{u\mathbf{k}}}{2} \right) \right)} \quad (1178)$$

$$-i \frac{\sum_{n < m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \left( -iv_{m\mathbf{k}}^{\Re} + v_{m\mathbf{k}}^{\Im} \coth \left( \frac{\beta_u \omega_{u\mathbf{k}}}{2} \right) \right) + \frac{\partial A_B}{\partial B_{mn}} B_{mn} \left( iv_{m\mathbf{k}}^{\Re} + v_{m\mathbf{k}}^{\Im} \coth \left( \frac{\beta_u \omega_{u\mathbf{k}}}{2} \right) \right) \right)}{2\omega_{u\mathbf{k}} \frac{\partial A_B}{\partial R_n} - \sum_{n < m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \coth \left( \frac{\beta_u \omega_{u\mathbf{k}}}{2} \right) + \frac{\partial A_B}{\partial B_{mn}} B_{mn} \coth \left( \frac{\beta_u \omega_{u\mathbf{k}}}{2} \right) \right)} \quad (1179)$$

$$= \frac{2g_{nu\mathbf{k}}\omega_{u\mathbf{k}}\frac{\partial A_{\mathbf{B}}}{\partial R_n}}{2\omega_{u\mathbf{k}}\frac{\partial A_{\mathbf{B}}}{\partial R_n} - \sum_{n < m} \left( \frac{\partial A_{\mathbf{B}}}{\partial B_{nm}} B_{nm} \coth\left(\frac{\beta_u \omega_{u\mathbf{k}}}{2}\right) + \frac{\partial A_{\mathbf{B}}}{\partial B_{mn}} B_{mn} \coth\left(\frac{\beta_u \omega_{u\mathbf{k}}}{2}\right) \right)} \quad (1180)$$

$$-\frac{\sum_{n < m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \left( v_{m\mathbf{k}} + v_{m\mathbf{k}} \coth \left( \frac{\beta \omega_{\mathbf{u}\mathbf{k}}}{2} \right) \right) + \frac{\partial A_B}{\partial B_{mn}} B_{mn} \left( -v_{m\mathbf{k}} + v_{m\mathbf{k}} \coth \left( \frac{\beta \omega_{\mathbf{u}\mathbf{k}}}{2} \right) \right) \right)}{2\omega_{\mathbf{u}\mathbf{k}} \frac{\partial A_B}{\partial R_n} - \sum_{n < m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \coth \left( \frac{\beta \omega_{\mathbf{u}\mathbf{k}}}{2} \right) + \frac{\partial A_B}{\partial B_{mn}} B_{mn} \coth \left( \frac{\beta \omega_{\mathbf{u}\mathbf{k}}}{2} \right) \right)} \quad (1181)$$

$$= \frac{2g_{nuk}\omega_{uk}\frac{\partial A_B}{\partial R_n} - \sum_{n < m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \left( v_{muk} + v_{muk} \coth \left( \frac{\beta_u \omega_{uk}}{2} \right) \right) + \frac{\partial A_B}{\partial B_{mn}} B_{mn} \left( -v_{muk} + v_{muk} \coth \left( \frac{\beta_u \omega_{uk}}{2} \right) \right) \right)}{2\omega_{uk}\frac{\partial A_B}{\partial R_n} - \sum_{n < m} \left( \frac{\partial A_B}{\partial B_{nm}} B_{nm} \coth \left( \frac{\beta_u \omega_{uk}}{2} \right) + \frac{\partial A_B}{\partial B_{mn}} B_{mn} \coth \left( \frac{\beta_u \omega_{uk}}{2} \right) \right)} \quad (1182)$$

### C. Master Equation

Let's consider that the initial state of the system is given by  $\rho(0) = |0\rangle\langle 0| \otimes \rho_B$ , as we can see this state is independent of the variation transformation:

$$e^V \rho(0) e^{-V} = \left( \sum_n |n\rangle\langle n| B_{n+} \right) (|0\rangle\langle 0| \otimes \rho_B) \left( \sum_n |n\rangle\langle n| B_{n+} \right) \quad (1183)$$

$$0 = (B_0^+ | 0 \rangle \langle 0 | B_0^-) \otimes \rho_B \quad (1184)$$

$$0 = \rho(0) \tag{1185}$$

We transform any operator  $O$  into the interaction picture in the following way:

$$\tilde{O} \equiv U^\dagger(t) O U(t) \quad (1186)$$

$$U(t) \equiv \mathcal{T} \exp \left( -i \int_0^t dt' \overline{H_S}(t') \right). \quad (1187)$$

Therefore:

$$\widetilde{\overline{\rho_S}}(t) = U^\dagger(t) \overline{\rho_S}(t) U(t), \text{ where} \quad (1188)$$

$$\overline{\rho_S}(t) = \text{Tr}_B(\bar{\rho}(t)) \quad (1189)$$

We can re-write the transformed interaction Hamiltonian operator using the following matrices:

$$\sigma_{nm,x} = |n\rangle\langle m| + |m\rangle\langle n| \quad (1190)$$

$$\sigma_{nm,y} = i(|n\rangle\langle m| - |m\rangle\langle n|) \quad (1191)$$

$$B_{nm,x} = \frac{B_{nm} + B_{mn}}{2} \quad (1192)$$

$$B_{nm,x} = \frac{B_{nm} - B_{mn}}{2i} \quad (1193)$$

We can proof that  $B_{nm} = B_{mn}^\dagger$

$$B_{mn}^\dagger = (B_{m+}B_{n-} - B_m B_n)^\dagger \quad (1194)$$

$$= B_{n-}^\dagger B_{m+}^\dagger - B_n B_m \quad (1195)$$

$$= B_{n+} B_{m-} - B_n B_m \quad (1196)$$

$$= B_{nm} \quad (1197)$$

So we can say that the set of matrices (1190) are hermetic. Re-writing the transformed interaction Hamiltonian using the set (1190) give us.

$$\overline{H_I} = \sum_{n \neq m} V_{nm}(t) |n\rangle\langle m| B_{nm} + \sum_n B_{z,n}(t) |n\rangle\langle n|, \quad (1198)$$

$$= \sum_n B_{z,n}(t) |n\rangle\langle n| + \sum_{n < m} (V_{nm}(t) |n\rangle\langle m| B_{nm} + V_{mn}(t) |m\rangle\langle n| B_{mn}) \quad (1199)$$

$$= \sum_n B_{z,n}(t) |n\rangle\langle n| + \sum_{n < m} \left( \Re(V_{nm}(t)) B_{nm} \left( \frac{\sigma_{nm,x} - i\sigma_{nm,y}}{2} \right) + iV_{nm}^\Im(t) B_{nm} \left( \frac{\sigma_{nm,x} - i\sigma_{nm,y}}{2} \right) \right) \quad (1200)$$

$$+ \Re(V_{nm}(t)) B_{mn} \left( \frac{\sigma_{nm,x} + i\sigma_{nm,y}}{2} \right) - iV_{nm}^\Im(t) B_{mn} \left( \frac{\sigma_{nm,x} + i\sigma_{nm,y}}{2} \right) \quad (1201)$$

$$= \sum_n B_{z,n}(t) |n\rangle\langle n| + \sum_{n < m} \left( \Re(V_{nm}(t)) \sigma_{nm,x} \left( \frac{B_{nm} + B_{mn}}{2} \right) + \Re(V_{nm}(t)) \sigma_{nm,y} \frac{i(B_{mn} - B_{nm})}{2} \right) \quad (1202)$$

$$+ i\Im(V_{nm}(t)) \sigma_{nm,x} \left( \frac{B_{nm} - B_{mn}}{2} \right) + \Im(V_{nm}(t)) \sigma_{nm,y} \left( \frac{B_{nm} + B_{mn}}{2} \right) \quad (1203)$$

$$= \sum_n B_{z,n}(t) |n\rangle\langle n| + \sum_{n < m} (\Re(V_{nm}(t)) \sigma_{nm,x} B_{nm,x} - \Im(V_{nm}(t)) \sigma_{nm,x} B_{nm,y} + \Re(V_{nm}(t)) \sigma_{nm,y} B_{nm,y} \quad (1204)$$

$$+ \Im(V_{nm}(t)) \sigma_{nm,y} B_{nm,x}) \quad (1205)$$

Let's define the set

$$P = \{(n, m) \in \mathbb{N}^2 | 0 \leq n, m \leq d-1 \wedge (n = m \vee n < m)\} \quad (1206)$$

Now consider the following set of operators,

$$A_{1,nm}(t) = \sigma_{nm,x}(1 - \delta_{mn}) \quad (1207)$$

$$A_{2,nm}(t) = \sigma_{nm,y}(1 - \delta_{mn}) \quad (1208)$$

$$A_{3,nm}(t) = \delta_{mn}|n\rangle\langle m| \quad (1209)$$

$$A_{4,nm}(t) = A_{2,mn}(t) \quad (1210)$$

$$A_{5,nm}(t) = A_{1,nm}(t) \quad (1211)$$

$$B_{1,nm}(t) = B_{nm,x} \quad (1212)$$

$$B_{2,nm}(t) = B_{nm,y} \quad (1213)$$

$$B_{3,nm}(t) = B_{z,n}(t) \quad (1214)$$

$$B_{4,nm}(t) = B_{1,nm}(t) \quad (1215)$$

$$B_{5,nm}(t) = B_{2,nm}(t) \quad (1216)$$

$$C_{1,nm}(t) = \Re(V_{nm}(t)) \quad (1217)$$

$$C_{2,nm}(t) = C_{1,nm}(t) \quad (1218)$$

$$C_{3,nm}(t) = 1 \quad (1219)$$

$$C_{4,nm}(t) = \Im(V_{nm}(t)) \quad (1220)$$

$$C_{5,nm}(t) = -\Im(V_{nm}(t)) \quad (1221)$$

The previous notation allows us to write the interaction Hamiltonian in  $\overline{H_I}(t)$  as:

$$\overline{H_I} = \sum_{j \in J, p \in P} C_{jp}(t) (A_{jp} \otimes B_{jp}(t)) \quad (1222)$$

Here  $J = \{1, 2, 3, 4, 5\}$  and  $P$  the set defined in (1206).

We write the interaction Hamiltonian transformed under (1186) as:

$$\widetilde{H_I}(t) = \sum_{j \in J, p \in P} C_{jp}(t) (\widetilde{A_{jp}}(t) \otimes \widetilde{B_{jp}}(t)) \quad (1223)$$

$$\widetilde{A_{jp}}(t) = U^\dagger(t) A_{jp} U(t) \quad (1224)$$

$$\widetilde{B_{jp}}(t) = e^{iH_B t} B_{jp}(t) e^{-iH_B t} \quad (1225)$$

Taking as reference state  $\rho_B$  and truncating at second order in  $H_I(t)$ , we obtain our master equation in the interaction picture:

$$\frac{d\widetilde{\rho_S}(t)}{dt} = - \int_0^t \text{Tr}_B [\widetilde{H_I}(t), [\widetilde{H_I}(s), \widetilde{\rho_S}(t) \rho_B]] ds \quad (1226)$$

Replacing the equation (1223) in (1226) we can obtain:

$$\frac{d\widetilde{\rho_S}(t)}{dt} = - \int_0^t \text{Tr}_B \left[ \widetilde{H}_I(t), \left[ \widetilde{H}_I(s), \widetilde{\rho_S}(t) \rho_B \right] \right] ds \quad (1227)$$

$$= - \int_0^t \text{Tr}_B \left[ \sum_{j \in J, p \in P} C_{jp}(t) \left( \widetilde{A}_{jp}(t) \otimes \widetilde{B}_{jp}(t) \right), \left[ \sum_{j' \in J, p' \in P} C_{j'p'}(s) \left( \widetilde{A}_{j'p'}(s) \otimes \widetilde{B}_{j'p'}(s) \right), \widetilde{\rho_S}(t) \rho_B \right] \right] ds \quad (1228)$$

$$= - \int_0^t \text{Tr}_B \left[ \sum_{j \in J, p \in P} C_{jp}(t) \left( \widetilde{A}_{jp}(t) \otimes \widetilde{B}_{jp}(t) \right), \sum_{j' \in J, p' \in P} C_{j'p'}(s) \left( \widetilde{A}_{j'p'}(s) \otimes \widetilde{B}_{j'p'}(s) \right) \widetilde{\rho_S}(t) \rho_B \right] \quad (1229)$$

$$- \widetilde{\rho_S}(t) \rho_B \sum_{j' \in J, p' \in P} C_{j'p'}(s) \left( \widetilde{A}_{j'p'}(s) \otimes \widetilde{B}_{j'p'}(s) \right) \Big] ds \quad (1230)$$

$$= - \int_0^t \text{Tr}_B \left( \sum_{j \in J, p \in P} C_{jp}(t) \left( \widetilde{A}_{jp}(t) \otimes \widetilde{B}_{jp}(t) \right) \sum_{j' \in J, p' \in P} C_{j'p'}(s) \left( \widetilde{A}_{j'p'}(s) \otimes \widetilde{B}_{j'p'}(s) \right) \widetilde{\rho_S}(t) \rho_B \right) \quad (1231)$$

$$- \sum_{j \in J, p \in P} C_{jp}(t) \left( \widetilde{A}_{jp}(t) \otimes \widetilde{B}_{jp}(t) \right) \widetilde{\rho_S}(t) \rho_B \sum_{j' \in J, p' \in P} C_{j'p'}(s) \left( \widetilde{A}_{j'p'}(s) \otimes \widetilde{B}_{j'p'}(s) \right) \quad (1232)$$

$$- \sum_{j' \in J, p' \in P} C_{j'p'}(s) \left( \widetilde{A}_{j'p'}(s) \otimes \widetilde{B}_{j'p'}(s) \right) \widetilde{\rho_S}(t) \rho_B \sum_{j \in J, p \in P} C_{jp}(t) \left( \widetilde{A}_{jp}(t) \otimes \widetilde{B}_{jp}(t) \right) \quad (1233)$$

$$+ \widetilde{\rho_S}(t) \rho_B \sum_{j' \in J, p' \in P} C_{j'p'}(s) \left( \widetilde{A}_{j'p'}(s) \otimes \widetilde{B}_{j'p'}(s) \right) \sum_{j \in J, p \in P} C_{jp}(t) \left( \widetilde{A}_{jp}(t) \otimes \widetilde{B}_{jp}(t) \right) \Big] ds \quad (1234)$$

In order to calculate the correlation functions we define:

$$\Lambda_{jpj'p'}(\tau) = \left\langle \widetilde{B}_{jp}(t) \widetilde{B}_{j'p'}(s) \right\rangle_B \quad (1235)$$

$$= \left\langle \widetilde{B}_{jp}(\tau) \widetilde{B}_{j'p'}(0) \right\rangle_B \quad (1236)$$

Here  $s \rightarrow t - \tau$  and  $\text{Tr}_B \left( \widetilde{B}_{jp}(t) \widetilde{B}_{j'p'}(s) \right) = \left\langle \widetilde{B}_{jp}(t) \widetilde{B}_{j'p'}(s) \right\rangle_B$ . To evaluate the trace respect to the bath we need to recall that our master equation depends of elements related to the bath and represented by the operators  $\widetilde{B}_{jp}(t)$  and elements related to the system given by  $\widetilde{A}_{jp}(t)$ . The systems considered are in different Hilbert spaces so  $\text{Tr} \left( \widetilde{A}_{jp}(t) \widetilde{B}_{j'p'}(t) \right) = \text{Tr} \left( \widetilde{A}_{jp}(t) \right) \text{Tr} \left( \widetilde{B}_{j'p'}(t) \right)$ . The correlation functions relevant of the master equation (1234) are:

$$\text{Tr}_B \left( \widetilde{B_{jp}}(t) \widetilde{B_{j'p'}}(s) \rho_B \right) = \left\langle \widetilde{B_{jp}}(t) \widetilde{B_{j'p'}}(s) \right\rangle_B \quad (1237)$$

$$= \left\langle \widetilde{B_{jp}}(0) \widetilde{B_{j'p'}}(0) \right\rangle_B \quad (1238)$$

$$= \Lambda_{jpj'p'}(\tau) \quad (1239)$$

$$\text{Tr}_B \left( \widetilde{B_{jp}}(t) \rho_B \widetilde{B_{j'p'}}(s) \right) = \text{Tr}_B \left( \widetilde{B_{j'p'}}(s) \widetilde{B_{jp}}(t) \rho_B \right) \quad (1240)$$

$$= \left\langle \widetilde{B_{j'p'}}(s) \widetilde{B_{jp}}(t) \right\rangle_B \quad (1241)$$

$$= \left\langle \widetilde{B_{j'p'}}(-\tau) \widetilde{B_{jp}}(0) \right\rangle_B \quad (1242)$$

$$= \Lambda_{j'p'jp}(-\tau) \quad (1243)$$

$$\text{Tr}_B \left( \widetilde{B_{j'p'}}(s) \rho_B \widetilde{B_{jp}}(t) \right) = \text{Tr}_B \left( \widetilde{B_{jp}}(t) \widetilde{B_{j'p'}}(s) \rho_B \right) \quad (1244)$$

$$= \left\langle \widetilde{B_{jp}}(t) \widetilde{B_{j'p'}}(s) \right\rangle_B \quad (1245)$$

$$= \left\langle \widetilde{B_{jp}}(\tau) \widetilde{B_{j'p'}}(0) \right\rangle_B \quad (1246)$$

$$= \Lambda_{jpj'p'}(\tau) \quad (1247)$$

$$\text{Tr}_B \left( \rho_B \widetilde{B_{j'p'}}(s) \widetilde{B_{jp}}(t) \right) = \text{Tr}_B \left( \widetilde{B_{j'p'}}(s) \widetilde{B_{jp}}(t) \rho_B \right) \quad (1248)$$

$$= \left\langle \widetilde{B_{j'p'}}(s) \widetilde{B_{jp}}(t) \right\rangle_B \quad (1249)$$

$$= \left\langle \widetilde{B_{j'p'}}(-\tau) \widetilde{B_{jp}}(0) \right\rangle_B \quad (1250)$$

$$= \Lambda_{j'p'jp}(-\tau) \quad (1251)$$

We made use of the cyclic property for the trace to evaluate the correlation functions, from the equations obtained in (1227) and (1234) and using the equations (1237)-(1251) we can re-write:

$$\frac{d\widetilde{\rho_S}(t)}{dt} = - \int_0^t \sum_{j,j',p,p'} \left( C_{jp}(t) C_{j'p'}(s) \left( \Lambda_{jpj'p'}(\tau) \widetilde{A_{jp}}(t) \widetilde{A_{j'p'}}(s) \widetilde{\rho_S}(t) - \Lambda_{j'p'jp}(-\tau) \widetilde{A_{jp}}(t) \widetilde{\rho_S}(t) \widetilde{A_{j'p'}}(s) \right) \right. \quad (1252)$$

$$\left. + C_{jp}(t) C_{j'p'}(s) \left( \Lambda_{j'p'jp}(-\tau) \widetilde{\rho_S}(t) \widetilde{A_{j'p'}}(s) \widetilde{A_{jp}}(t) - \Lambda_{jpj'p'}(\tau) \widetilde{A_{j'p'}}(s) \widetilde{\rho_S}(t) \widetilde{A_{jp}}(t) \right) \right) ds \quad (1253)$$

$$= - \int_0^t \sum_{jj'pp'} \left( C_{jp}(t) C_{j'p'}(s) \left( \Lambda_{jpj'p'}(\tau) \left[ \widetilde{A_{jp}}(t), \widetilde{A_{j'p'}}(s) \widetilde{\rho_S}(t) \right] + \Lambda_{j'p'jp}(-\tau) \left[ \widetilde{\rho_S}(t) \widetilde{A_{j'p'}}(s), \widetilde{A_{jp}}(t) \right] \right) \right) \quad (1254)$$

Rearranging and identifying the commutators allow us to write a more simplified version

$$\frac{d\widetilde{\rho_S}(t)}{dt} = - \int_0^t \sum_{jj'pp'} \left( C_{jp}(t) C_{j'p'}(t-\tau) \left( \Lambda_{jpj'p'}(\tau) \left[ A_{jp}(t), A_{j'p'}(t-\tau, t) \widetilde{\rho_S}(t) \right] + \Lambda_{j'p'jp}(-\tau) \left[ \widetilde{\rho_S}(t) A_{j'p'}(t-\tau, t), A_{jp}(t) \right] \right) \right) d\tau - i [H_S(t), \widetilde{\rho_S}(t)] \quad (1255)$$

For this case we used that  $A_{jp}(t-\tau, t) = U(t) U^\dagger(t-\tau) A_{jp}(t) U(t-\tau) U^\dagger(t)$ . This is a non-Markovian equation.

## VII. TIME-DEPENDENT MULTI-SITE MODEL WITH ONE BATH COUPLING

Let's consider the following Hamiltonian for a system of d-levels (qudit). We start with a time-dependent Hamiltonian of the form:



$$H(t) = H_S(t) + H_I + H_B, \quad (1256)$$

$$H_S(t) = \sum_{n=0} \varepsilon_n(t) |n\rangle\langle n| + \sum_{n \neq m} V_{nm}(t) |n\rangle\langle m|, \quad (1257)$$

$$H_I = \left( \sum_{n=0} \mu_n(t) |n\rangle\langle n| \right) \left( \sum_{\mathbf{k}} g_{\mathbf{k}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) \right), \quad (1258)$$

$$H_B = \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}}. \quad (1259)$$

We will start with a system-bath coupling operator of the form  $\sum_{n=0} \mu_n(t) |n\rangle\langle n|$ .

### A. Variational Transformation

We consider the following operator:

$$V = \left( \sum_{n=1} |n\rangle\langle n| \right) \left( \sum_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} (b_{\mathbf{k}}^\dagger - b_{\mathbf{k}}) \right) \quad (1260)$$

At first let's obtain  $e^V$  under the transformation (1260), consider  $\hat{\varphi} = \sum_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} (b_{\mathbf{k}}^\dagger - b_{\mathbf{k}})$ :

$$e^V = e^{\sum_{n=1} |n\rangle\langle n| \hat{\varphi}} \quad (1261)$$

$$= \mathbb{I} + \sum_{n=1} |n\rangle\langle n| \hat{\varphi} + \frac{(\sum_{n=1} |n\rangle\langle n| \hat{\varphi})^2}{2!} + \dots \quad (1262)$$

$$= \mathbb{I} + \sum_{n=1} |n\rangle\langle n| \hat{\varphi} + \frac{\sum_{n=1} |n\rangle\langle n| \hat{\varphi}^2}{2!} + \dots \quad (1263)$$

$$= \mathbb{I} - \sum_{n=1} |n\rangle\langle n| + \sum_{n=1} |n\rangle\langle n| \left( \mathbb{I} + \hat{\varphi} + \frac{\hat{\varphi}^2}{2!} + \dots \right) \quad (1264)$$

$$= |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| e^{\hat{\varphi}} \quad (1265)$$

$$= |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^+ \quad (1266)$$

Given that  $[b_{\mathbf{k}'}^\dagger - b_{\mathbf{k}'}^\dagger, b_{\mathbf{k}}^\dagger - b_{\mathbf{k}}] = 0$  if  $\mathbf{k}' \neq \mathbf{k}$  then we can proof using the Zassenhaus formula and defining  $D\left(\pm \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}}\right) = e^{\pm \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} (b_{\mathbf{k}}^\dagger - b_{\mathbf{k}})}$  in the same way than (23):

$$e^{\sum_{\mathbf{k}} \pm \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} (b_{\mathbf{k}}^\dagger - b_{\mathbf{k}})} = \prod_{\mathbf{k}} e^{\pm \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} (b_{\mathbf{k}}^\dagger - b_{\mathbf{k}})} \quad (1267)$$

$$= \prod_{\mathbf{k}} D\left(\pm \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}}\right) \quad (1268)$$

$$= B_{\pm} \quad (1269)$$

As we can see  $e^{-V} = |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B$ . because this form imposes that  $e^{-V} e^V = \mathbb{I}$  and the inverse of a operator is unique. This allows us to write the canonical transformation in the following explicit way:

$$e^V A e^{-V} = \left( |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^+ \right) A \left( |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^- \right) \quad (1270)$$

Now let's obtain the canonical transformation of the principal elements of the Hamiltonian (1256):

$$\overline{|0\rangle\langle 0|} = \left( |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^+ \right) |0\rangle\langle 0| \left( |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^- \right), \quad (1271)$$

$$= |0\rangle\langle 0|, \quad (1272)$$

$$\overline{|m\rangle\langle n|} = \left( |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^+ \right) |m\rangle\langle n| \left( |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^- \right), \quad (1273)$$

$$= |m\rangle\langle m| B^+ |m\rangle\langle n| n\rangle\langle n| B^-, \quad (1274)$$

$$= |m\rangle\langle n|, \quad m \neq 0, \quad n \neq 0, \quad (1275)$$

$$\overline{|0\rangle\langle m|} = \left( |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^+ \right) |0\rangle\langle m| \left( |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^- \right), \quad (1276)$$

$$= |0\rangle\langle m| B^- \quad m \neq 0, \quad (1277)$$

$$\overline{|m\rangle\langle 0|} = \left( |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^+ \right) |m\rangle\langle 0| \left( |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^- \right) \quad (1278)$$

$$= |0\rangle\langle m| B^+ \quad m \neq 0, \quad (1279)$$

$$\overline{\sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}}} = \left( |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^+ \right) \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} \left( |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^- \right) \quad (1280)$$

$$= |0\rangle\langle 0| \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + \sum_{n=1} |n\rangle\langle n| \sum_{\mathbf{k}} \omega_{\mathbf{k}} B^+ b_{\mathbf{k}}^\dagger b_{\mathbf{k}} B^- \quad (1281)$$

$$= |0\rangle\langle 0| \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + \sum_{n=1} |n\rangle\langle n| \sum_{\mathbf{k}} \omega_{\mathbf{k}} \left( B^+ b_{\mathbf{k}}^\dagger B^- \right) \left( B^+ b_{\mathbf{k}} B^- \right) \quad (1282)$$

$$= |0\rangle\langle 0| \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + \sum_{n=1} |n\rangle\langle n| \sum_{\mathbf{k}} \omega_{\mathbf{k}} \left( b_{\mathbf{k}}^\dagger - \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} \right) \left( b_{\mathbf{k}} - \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} \right) \quad (1283)$$

$$= |0\rangle\langle 0| \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + \sum_{n=1} |n\rangle\langle n| \sum_{\mathbf{k}} \omega_{\mathbf{k}} \left( b_{\mathbf{k}}^\dagger b_{\mathbf{k}} - \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) + \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} \right) \quad (1284)$$

$$= \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + \sum_{n=1} |n\rangle\langle n| \sum_{\mathbf{k}} \omega_{\mathbf{k}} \left( \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} - \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) \right) \quad (1285)$$

$$= \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + \sum_{n=1} |n\rangle\langle n| \sum_{\mathbf{k}} \omega_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} - \sum_{n=1} |n\rangle\langle n| \omega_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) \quad (1286)$$

The transformed Hamiltonians of the equations (1257) to (1259) written in terms of (1271) to (1286) are:

$$\overline{H_S(t)} = \overline{\sum_{n=0} \varepsilon_n(t) |n\rangle\langle n| + \sum_{n \neq m} V_{nm}(t) |n\rangle\langle m|} \quad (1287)$$

$$= \overline{\sum_{n=0} \varepsilon_n(t) |n\rangle\langle n|} + \overline{\sum_{n \neq m} V_{nm}(t) |n\rangle\langle m|} \quad (1288)$$

$$= \sum_{n=0} \varepsilon_n(t) |n\rangle\langle n| + \sum_{n=1} (V_{0n}(t) |0\rangle\langle n| + V_{n0}(t) |n\rangle\langle 0|) + \sum_{m,n \neq 0} V_{mn}(t) |m\rangle\langle n| \quad (1289)$$

$$= \sum_{n=0} \varepsilon_n(t) |n\rangle\langle n| + \sum_{n=1} (V_{0n}(t) \overline{|0\rangle\langle n|} + V_{n0}(t) \overline{|n\rangle\langle 0|}) + \sum_{m,n \neq 0} V_{mn}(t) \overline{|m\rangle\langle n|} \quad (1290)$$

$$= \sum_{n=0} \varepsilon_n(t) |n\rangle\langle n| + \sum_{n=1} (V_{0n}(t) B^- |0\rangle\langle n| + V_{n0}(t) B^+ |n\rangle\langle 0|) + \sum_{m,n \neq 0} V_{mn}(t) |m\rangle\langle n| \quad (1291)$$

$$= \sum_{n=0} \varepsilon_n(t) |n\rangle\langle n| + \sum_{n=1} (V_{0n}(t) |0\rangle\langle n| B^- + V_{n0}(t) |n\rangle\langle 0| B^+) + \sum_{m,n \neq 0} V_{mn}(t) |m\rangle\langle n| \quad (1292)$$

$$\overline{H_I} = \left( |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^+ \right) \left( \left( \sum_{n=0} \mu_n(t) |n\rangle\langle n| \right) \left( \sum_{\mathbf{k}} g_{\mathbf{k}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) \right) \right) \left( |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^- \right) \quad (1293)$$

$$= \left( \mu_0(t) |0\rangle\langle 0| + \sum_{n=1} \mu_n(t) |n\rangle\langle n| B^+ \right) \left( \sum_{\mathbf{k}} g_{\mathbf{k}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) \right) \left( |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^- \right) \quad (1294)$$

$$= \mu_0(t) |0\rangle\langle 0| \sum_{\mathbf{k}} g_{\mathbf{k}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) + \sum_{n=1} \mu_n(t) |n\rangle\langle n| \sum_{\mathbf{k}} g_{\mathbf{k}} B^+ (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) B^- \quad (1295)$$

$$= \mu_0(t) |0\rangle\langle 0| \sum_{\mathbf{k}} g_{\mathbf{k}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) + \sum_{n=1} \mu_n(t) |n\rangle\langle n| \sum_{\mathbf{k}} g_{\mathbf{k}} \left( b_{\mathbf{k}}^\dagger + b_{\mathbf{k}} - 2 \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} \right) \quad (1296)$$

$$\overline{H_B} = \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + \sum_{n=1} |n\rangle\langle n| \sum_{\mathbf{k}} \omega_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} - \sum_{n=1} |n\rangle\langle n| \omega_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) \quad (1297)$$

Joining this terms allow us to write:

$$\overline{H} = \sum_{n=0} \varepsilon_n(t) |n\rangle\langle n| + \sum_{n=1} (V_{0n}(t) |0\rangle\langle n| B^- + V_{n0}(t) |n\rangle\langle 0| B^+) + \sum_{m,n \neq 0} V_{mn}(t) |m\rangle\langle n| \quad (1298)$$

$$+ \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + \sum_{n=1} |n\rangle\langle n| \sum_{\mathbf{k}} \omega_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} - \sum_{n=1} |n\rangle\langle n| \omega_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) \quad (1299)$$

$$+ \sum_{n=0} \mu_n(t) |n\rangle\langle n| \sum_{\mathbf{k}} g_{\mathbf{k}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) - \sum_{n=1} \mu_n(t) |n\rangle\langle n| \sum_{\mathbf{k}} 2g_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} \quad (1300)$$

$$= \sum_{n=0} \varepsilon_n(t) |n\rangle\langle n| + \sum_{n=1} (V_{0n}(t) |0\rangle\langle n| B^- + V_{n0}(t) |n\rangle\langle 0| B^+) + \sum_{m,n \neq 0} V_{mn}(t) |m\rangle\langle n| \quad (1301)$$

$$+ \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + \sum_{n=1} |n\rangle\langle n| \sum_{\mathbf{k}} \left( \omega_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} - 2\mu_n(t) g_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} \right) + \mu_0(t) |0\rangle\langle 0| \sum_{\mathbf{k}} g_{\mathbf{k}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) \quad (1302)$$

$$+ \sum_{n=1} |n\rangle\langle n| \sum_{\mathbf{k}} \left( g_{\mathbf{k}} \mu_n(t) - \omega_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} \right) (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) \quad (1303)$$

Let's define the following functions:

$$R_n(t) = \sum_{\mathbf{k}} \left( \omega_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} - 2\mu_n(t) g_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} \right) \quad (1304)$$

$$= \sum_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} \left( \omega_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} - 2\mu_n(t) g_{\mathbf{k}} \right) \quad (1305)$$

$$B_{z,n}(t) = \sum_{\mathbf{k}} \left( g_{\mathbf{k}} \mu_n(t) - \omega_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} \right) (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) \quad (1306)$$

Using the previous functions we have that (1303) can be re-written in the following way:

$$\overline{H} = \sum_{n=0} \varepsilon_n(t) |n\rangle\langle n| + \sum_{n=1} (V_{0n}(t) |0\rangle\langle n| B^- + V_{n0}(t) |n\rangle\langle 0| B^+) + \sum_{m,n \neq 0} V_{mn}(t) |m\rangle\langle n| \quad (1307)$$

$$+ \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} + \sum_{n=1} R_n |n\rangle\langle n| + \sum_{n=1} B_{z,n} |n\rangle\langle n| + \mu_0(t) |0\rangle\langle 0| \sum_{\mathbf{k}} g_{\mathbf{k}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) \quad (1308)$$

Now in order to separate the elements of the hamiltonian (1308) let's follow the references of the equations (236) and (225) to separate the hamiltonian like:

$$\overline{H_S}(t) = \sum_{n=0} \varepsilon_n(t) |n\rangle\langle n| + B \sum_{n=1} (V_{0n}(t) |0\rangle\langle n| + V_{n0}(t) |n\rangle\langle 0|) + \sum_{m,n \neq 0} V_{mn}(t) |m\rangle\langle n| + \sum_{n=1} R_n |n\rangle\langle n| \quad (1309)$$

$$\overline{H_I} = \sum_{n=1} B_{z,n} |n\rangle\langle n| + \mu_0(t) |0\rangle\langle 0| \sum_{\mathbf{k}} g_{\mathbf{k}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) + \sum_{n=1} (V_{0n}(t) |0\rangle\langle n| (B^- - B) + V_{n0}(t) |n\rangle\langle 0| (B^+ - B)), \quad (1310)$$

$$\overline{H_B} = \sum_{\mathbf{k}} \omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}} \quad (1311)$$

Here B is given by:

$$\begin{aligned} B &= \langle B^+ \rangle \\ &= \langle B^- \rangle \end{aligned}$$

The transformed Hamiltonian can be written in function of the following set of hermitian operators:

$$\sigma_{nm,x} = |n\rangle\langle m| + |m\rangle\langle n| \quad (1312)$$

$$\sigma_{nm,y} = i(|n\rangle\langle m| - |m\rangle\langle n|) \quad (1313)$$

$$B_x = \frac{B^+ + B^- - 2B}{2} \quad (1314)$$

$$B_y = \frac{B^- - B^+}{2i} \quad (1315)$$

Using this set of hermitian operators to write the Hamiltonians (1257)-(1259)

$$\overline{H_S(t)} = \varepsilon_0(t) |0\rangle\langle 0| + \sum_{n=1} (\varepsilon_n(t) + R_n) |n\rangle\langle n| + B \sum_{n=1} (V_{0n}(t) |0\rangle\langle n| + V_{n0}(t) |n\rangle\langle 0|) + \sum_{m,n \neq 0} V_{mn}(t) |m\rangle\langle n| \quad (1316)$$

$$= \varepsilon_0(t) |0\rangle\langle 0| + B \sum_{n=1} (V_{0n}(t) |0\rangle\langle n| + V_{n0}(t) |n\rangle\langle 0|) + \sum_{0 < m < n} (V_{mn}(t) |m\rangle\langle n| + V_{nm}(t) |n\rangle\langle m|) \quad (1317)$$

$$+ \sum_{n=1} (\varepsilon_n(t) + R_n) |n\rangle\langle n| \quad (1318)$$

$$= \sum_{0 < m < n} ((\Re(V_{mn}(t)) + i\Im(V_{mn}(t))) |m\rangle\langle n| + (\Re(V_{mn}(t)) - i\Im(V_{mn}(t))) |n\rangle\langle m|) + \varepsilon_0(t) |0\rangle\langle 0| \quad (1319)$$

$$+ B \sum_{n=1} (V_{0n}(t) |0\rangle\langle n| + V_{n0}(t) |n\rangle\langle 0|) + \sum_{n=1} (\varepsilon_n(t) + R_n) |n\rangle\langle n| \quad (1320)$$

$$= \sum_{0 < m < n} \left( (\Re(V_{nm}(t)) + i\Im(V_{mn}(t))) \frac{\sigma_{nm,x} - i\sigma_{nm,y}}{2} + (\Re(V_{nm}(t)) - i\Im(V_{mn}(t))) \frac{\sigma_{nm,x} + i\sigma_{nm,y}}{2} \right) \quad (1321)$$

$$+ B \sum_{n=1} \left( V_{0n}(t) \frac{\sigma_{0n,x} - i\sigma_{0n,y}}{2} + V_{n0}(t) \frac{\sigma_{0n,x} + i\sigma_{0n,y}}{2} \right) + \varepsilon_0(t) |0\rangle\langle 0| + \sum_{n=1} (\varepsilon_n(t) + R_n) |n\rangle\langle n| \quad (1322)$$

$$= \sum_{0 < m < n} (\Re(V_{nm}(t)) \sigma_{nm,x} + \Im(V_{nm}(t)) \sigma_{nm,y}) + B \sum_{n=1} (\Re(V_{0n}(t)) \sigma_{0n,x} + \Im(V_{mn}(t)) \sigma_{0n,y}) \quad (1323)$$

$$+ \varepsilon_0(t) |0\rangle\langle 0| + \sum_{n=1} (\varepsilon_n(t) + R_n) |n\rangle\langle n| \quad (1324)$$

$$\overline{H_I(t)} = \sum_{n=1} B_{z,n} |n\rangle\langle n| + \mu_0(t) |0\rangle\langle 0| \sum_{\mathbf{k}} g_{\mathbf{k}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) + \sum_{n=1} (V_{0n}(t) |0\rangle\langle n| (B^- - B) + V_{n0}(t) |n\rangle\langle 0| (B^+ - B)) \quad (1325)$$

$$= \sum_{n=1} \left( (\Re(V_{0n}(t)) + i\Im(V_{0n}(t))) (B^- - B) \frac{\sigma_{0n,x} - i\sigma_{0n,y}}{2} + (\Re(V_{0n}(t)) - i\Im(V_{0n}(t))) (B^+ - B) \frac{\sigma_{0n,x} + i\sigma_{0n,y}}{2} \right) \quad (1326)$$

$$+ \sum_{n=1} B_{z,n} |n\rangle\langle n| + \mu_0(t) |0\rangle\langle 0| \sum_{\mathbf{k}} g_{\mathbf{k}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) \quad (1327)$$

$$= \sum_{n=1} B_{z,n} |n\rangle\langle n| + \sum_{n=1} \left( \frac{\sigma_{0n,x}}{2} ((B^- - B) (\Re(V_{0n}(t)) + i\Im(V_{0n}(t))) + (B^+ - B) (\Re(V_{0n}(t)) - i\Im(V_{0n}(t)))) \right) \quad (1328)$$

$$+ \frac{i\sigma_{0n,y}}{2} ((B^+ - B) (\Re(V_{0n}(t)) - i\Im(V_{0n}(t))) - (B^- - B) (\Re(V_{0n}(t)) + i\Im(V_{0n}(t)))) \quad (1329)$$

$$+ \mu_0(t) |0\rangle\langle 0| \sum_{\mathbf{k}} g_{\mathbf{k}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) \quad (1330)$$

$$= \mu_0(t) |0\rangle\langle 0| \sum_{\mathbf{k}} g_{\mathbf{k}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) + \sum_{n=1} \left( \frac{\sigma_{0n,x}}{2} (B^+ + B^- - 2B) \Re(V_{0n}(t)) + i(B^- - B - B^+ + B) \Im(V_{0n}(t)) \right) \quad (1331)$$

$$+ \frac{i\sigma_{0n,y}}{2} ((B^+ - B - B^- + B) \Re(V_{0n}(t)) + i(B - B^- + B - B^+) \Im(V_{0n}(t))) + \sum_{n=1} B_{z,n} |n\rangle\langle n| \quad (1332)$$

$$= \sum_{n=1} B_{z,n} |n\rangle\langle n| + \mu_0(t) |0\rangle\langle 0| \sum_{\mathbf{k}} g_{\mathbf{k}} (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) + \sum_{n=1} (\sigma_{0n,x} (B_x \Re(V_{0n}(t)) - B_y \Im(V_{0n}(t))) \quad (1333)$$

$$+ \sigma_{0n,y} (B_y \Re(V_{0n}(t)) + B_x \Im(V_{0n}(t)))) \quad (1334)$$

## B. Free-energy minimization

As first approach let's consider the minimization of the free-energy through the Feynman-Bogoliubov inequality

$$A \leq A_B \equiv -\frac{1}{\beta} \ln \left( \text{Tr} \left( e^{-\beta(\overline{H}_S + \overline{H}_B)} \right) \right) + \langle \overline{H}_I \rangle_{\overline{H}_S + \overline{H}_B} + O \left( \langle \overline{H}_I^2 \rangle_{\overline{H}_S + \overline{H}_B} \right). \quad (1335)$$

Taking the equations (246)-(254) and given that  $\text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right) = C(R_1, R_2, \dots, R_{d-1}, B)$ , where each  $R_i$  and  $B$  depend of the set of variational parameters  $\{v_{\mathbf{k}}\}$ . From (254) and using the chain rule we obtain that:

$$\frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial v_{\mathbf{k}}} = \frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial B} \frac{\partial B}{\partial v_{\mathbf{k}}} + \sum_{n=1} \frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial R_n} \frac{\partial R_n}{\partial v_{\mathbf{k}}}, \quad (1336)$$

$$= 0 \quad (1337)$$

Let's recall the equations (1304) and (1306), we can write them in terms of the variational parameters

$$B = \exp \left( - (1/2) \sum_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}^2} \coth(\beta \omega_{\mathbf{k}}/2) \right) \quad (1338)$$

$$R_n = \sum_{\mathbf{k}} \omega_{\mathbf{k}}^{-1} (v_{\mathbf{k}} - 2\mu_n(t) g_{\mathbf{k}} v_{\mathbf{k}}) \quad (1339)$$

The derivates needed to obtain the set of variational parameter are given by:

$$\frac{\partial B}{\partial v_{\mathbf{k}}} = -\frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}^2} \coth(\beta \omega_{\mathbf{k}}/2) B \quad (1340)$$

$$\frac{\partial R_n}{\partial v_{\mathbf{k}}} = \omega_{\mathbf{k}}^{-1} (2v_{\mathbf{k}} - 2\mu_n(t) g_{\mathbf{k}}) \quad (1341)$$

Introducing this derivates in the equation (1336) give us:

$$\frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial v_{\mathbf{k}}} = \frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial B} \left( -\frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}^2} \coth(\beta \omega_{\mathbf{k}}/2) B \right) + \sum_{n=1} \frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial R_n} \omega_{\mathbf{k}}^{-1} (2v_{\mathbf{k}} - 2\mu_n(t) g_{\mathbf{k}}) \quad (1342)$$

$$= v_{\mathbf{k}} \left( \frac{2}{\omega_{\mathbf{k}}} \sum_{n=1} \frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial R_n} - \frac{\coth(\beta \omega_{\mathbf{k}}/2) B}{\omega_{\mathbf{k}}^2} \frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial B} \right) - \frac{2g_{\mathbf{k}}}{\omega_{\mathbf{k}}} \sum_{n=1} \frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial R_n} \mu_n(t) \quad (1343)$$

We can obtain the variational parameters:

$$v_{\mathbf{k}} = \frac{\frac{2g_{\mathbf{k}}}{\omega_{\mathbf{k}}} \sum_{n=1} \frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial R_n} \mu_n(t)}{\frac{2}{\omega_{\mathbf{k}}} \sum_{n=1} \frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial R_n} - \frac{\coth(\beta \omega_{\mathbf{k}}/2) B}{\omega_{\mathbf{k}}^2} \frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial B}} \quad (1344)$$

$$= \frac{2g_{\mathbf{k}} \omega_{\mathbf{k}} \sum_{n=1} \frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial R_n} \mu_n(t)}{2\omega_{\mathbf{k}} \sum_{n=1} \frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial R_n} - B \coth(\beta \omega_{\mathbf{k}}/2) \frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial B}} \quad (1345)$$

Now taking  $v_{\mathbf{k}} = g_{\mathbf{k}} v_{\mathbf{k}}$  then we can obtain  $v_{\mathbf{k}}$  like:

$$v_{\mathbf{k}} = \frac{2\omega_{\mathbf{k}} \sum_{n=1} \frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial R_n} \mu_n(t)}{2\omega_{\mathbf{k}} \sum_{n=1} \frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial R_n} - B \coth(\beta \omega_{\mathbf{k}}/2) \frac{\partial \text{Tr} \left( e^{-\beta \overline{H}_S(t)} \right)}{\partial B}}. \quad (1346)$$

### C. Master Equation

Let's consider that the initial state of the system is given by  $\rho(0) = |0\rangle\langle 0| \otimes \rho_B$ , as we can see this state is independent of the variational transformation:

$$e^V \rho(0) e^{-V} = \left( |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^+ \right) (|0\rangle\langle 0| \otimes \rho_B) \left( |0\rangle\langle 0| + \sum_{n=1} |n\rangle\langle n| B^- \right) \quad (1347)$$

$$0 = |0\rangle\langle 0| \otimes \rho_B \quad (1348)$$

$$0 = \rho(0) \quad (1349)$$

We transform any operator  $O$  into the interaction picture in the following way:

$$\tilde{O} \equiv U^\dagger(t) O U(t) \quad (1350)$$

$$U(t) \equiv \mathcal{T} \exp \left( -i \int_0^t dt' \overline{H_S}(t') \right). \quad (1351)$$

Therefore:

$$\widetilde{\overline{\rho_S}}(t) = U^\dagger(t) \overline{\rho_S}(t) U(t), \text{ where} \quad (1352)$$

$$\overline{\rho_S}(t) = \text{Tr}_B(\tilde{\rho}(t)) \quad (1353)$$

We can re-write the transformed interaction Hamiltonian operator like:

$$\overline{H_I}(t) = B_{z,0} |0\rangle\langle 0| + \sum_{n=1} (\Re(V_{0n}(t)) B_x \sigma_{0n,x} + \Re(V_{0n}(t)) B_y \sigma_{0n,y} + B_{z,n} |n\rangle\langle n|) \quad (1354)$$

$$+ \Im(V_{0n}(t)) B_x \sigma_{0n,y} - \Im(V_{0n}(t)) B_y \sigma_{0n,x}) \quad (1355)$$

where

$$B_{z,0} = \sum_{\mathbf{k}} g_{\mathbf{k}} \mu_0(t) (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) \quad (1356)$$

$$B_{z,n} = \sum_{\mathbf{k}} \left( g_{\mathbf{k}} \mu_n(t) - \omega_{\mathbf{k}} \frac{v_{\mathbf{k}}}{\omega_{\mathbf{k}}} \right) (b_{\mathbf{k}}^\dagger + b_{\mathbf{k}}) \text{ if } n \neq 0 \quad (1357)$$

Now consider the following set of operators:

$$A_{1n}(t) = \sigma_{0n,x} \quad (1358)$$

$$A_{2n}(t) = \sigma_{0n,y} \quad (1359)$$

$$A_{3n}(t) = |n\rangle\langle n| \quad (1360)$$

$$A_{4n}(t) = A_{2n}(t) \quad (1361)$$

$$A_{5n}(t) = A_{1n}(t) \quad (1362)$$

$$B_{1n}(t) = B_x \quad (1363)$$

$$B_{2n}(t) = B_y \quad (1364)$$

$$B_{3n}(t) = B_{z,n} \quad (1365)$$

$$B_{4n}(t) = B_{1n}(t) \quad (1366)$$

$$B_{5n}(t) = B_{2n}(t) \quad (1367)$$

$$C_{10}(t) = 0 \quad (1368)$$

$$C_{20}(t) = 0 \quad (1369)$$

$$C_{40}(t) = 0 \quad (1370)$$

$$C_{50}(t) = 0 \quad (1371)$$

$$C_{30}(t) = 1 \quad (1372)$$

$$C_{1n}(t) = \Re(V_{0n}(t)) \quad (1373)$$

$$C_{2n}(t) = C_{1n}(t) \quad (1374)$$

$$C_{3n}(t) = 1 \quad (1375)$$

$$C_{4n}(t) = \Im(V_{0n}(t)) \quad (1376)$$

$$C_{5n}(t) = -\Im(V_{0n}(t)) \quad (1377)$$

The previous notation allows us to write the interaction Hamiltonian in  $\overline{H}_I(t)$  as:

$$\overline{H}_I = \sum_{j \in J} \sum_{n=1} C_{jn}(t) (A_{jn} \otimes B_{jn}(t)) \quad (1378)$$

Here  $J = \{1, 2, 3, 4, 5\}$ .

We write the interaction Hamiltonian transformed under (1350) as:

$$\widetilde{H}_I(t) = \sum_{j \in J} \sum_{n=1} C_{jn}(t) \left( \widetilde{A}_{jn}(t) \otimes \widetilde{B}_{jn}(t) \right) \quad (1379)$$

$$\widetilde{A}_i(t) = U^\dagger(t) A_i U(t) \quad (1380)$$

$$\widetilde{B}_i(t) = e^{iH_B t} B_i(t) e^{-iH_B t} \quad (1381)$$

Taking as reference state  $\rho_B$  and truncating at second order in  $H_I(t)$ , we obtain our master equation in the interaction picture:

$$\frac{d\widetilde{\rho}_S(t)}{dt} = - \int_0^t \text{Tr}_B \left[ \widetilde{H}_I(t), \left[ \widetilde{H}_I(s), \widetilde{\rho}_S(t) \rho_B \right] \right] ds \quad (1382)$$

Replacing the equation (1379) in (1382) we can obtain:



$$\frac{d\widetilde{\rho_S}(t)}{dt} = - \int_0^t \text{Tr}_B \left[ \widetilde{H}_I(t), \left[ \widetilde{H}_I(s), \widetilde{\rho_S}(t) \rho_B \right] \right] ds \quad (1383)$$

$$= - \int_0^t \text{Tr}_B \left[ \sum_{j \in J} \sum_{n=1} C_{jn}(t) \left( \widetilde{A}_{jn}(t) \otimes \widetilde{B}_{jn}(t) \right), \left[ \sum_{j' \in J} \sum_{n'=1} C_{j'n'}(s) \left( \widetilde{A}_{j'n'}(s) \otimes \widetilde{B}_{j'n'}(s) \right), \widetilde{\rho_S}(t) \rho_B \right] \right] ds \quad (1384)$$

$$= - \int_0^t \text{Tr}_B \left[ \sum_{j \in J} \sum_{n=1} C_{jn}(t) \left( \widetilde{A}_{jn}(t) \otimes \widetilde{B}_{jn}(t) \right), \sum_{j' \in J} \sum_{n'=1} C_{j'n'}(s) \left( \widetilde{A}_{j'n'}(s) \otimes \widetilde{B}_{j'n'}(s) \right) \widetilde{\rho_S}(t) \rho_B \right] ds \quad (1385)$$

$$- \widetilde{\rho_S}(t) \rho_B \sum_{j' \in J} \sum_{n'=1} C_{j'n'}(s) \left( \widetilde{A}_{j'n'}(s) \otimes \widetilde{B}_{j'n'}(s) \right) \Big] ds \quad (1386)$$

$$= - \int_0^t \text{Tr}_B \left( \sum_{j \in J} \sum_{n=1} C_{jn}(t) \left( \widetilde{A}_{jn}(t) \otimes \widetilde{B}_{jn}(t) \right) \sum_{j' \in J} \sum_{n'=1} C_{j'n'}(s) \left( \widetilde{A}_{j'n'}(s) \otimes \widetilde{B}_{j'n'}(s) \right) \widetilde{\rho_S}(t) \rho_B \right) ds \quad (1387)$$

$$- \sum_{j \in J} \sum_{n=1} C_{jn}(t) \left( \widetilde{A}_{jn}(t) \otimes \widetilde{B}_{jn}(t) \right) \widetilde{\rho_S}(t) \rho_B \sum_{j' \in J} \sum_{n'=1} C_{j'n'}(s) \left( \widetilde{A}_{j'n'}(s) \otimes \widetilde{B}_{j'n'}(s) \right) \quad (1388)$$

$$- \sum_{j' \in J} \sum_{n'=1} C_{j'n'}(s) \left( \widetilde{A}_{j'n'}(s) \otimes \widetilde{B}_{j'n'}(s) \right) \widetilde{\rho_S}(t) \rho_B \sum_{j \in J} \sum_{n=1} C_{jn}(t) \left( \widetilde{A}_{jn}(t) \otimes \widetilde{B}_{jn}(t) \right) \quad (1389)$$

$$+ \widetilde{\rho_S}(t) \rho_B \sum_{j' \in J} \sum_{n'=1} C_{j'n'}(s) \left( \widetilde{A}_{j'n'}(s) \otimes \widetilde{B}_{j'n'}(s) \right) \sum_{j \in J} \sum_{n=1} C_{jn}(t) \left( \widetilde{A}_{jn}(t) \otimes \widetilde{B}_{jn}(t) \right) \Big) ds \quad (1390)$$

In order to calculate the correlation functions we define:

$$\Lambda_{jn j'n'}(\tau) = \left\langle \widetilde{B}_{jn}(t) \widetilde{B}_{j'n'}(s) \right\rangle_B \quad (1391)$$

$$= \left\langle \widetilde{B}_{jn}(\tau) \widetilde{B}_{j'n'}(0) \right\rangle_B \quad (1392)$$

Here  $s \rightarrow t - \tau$  and  $\text{Tr}_B \left( \widetilde{B}_{jn}(t) \widetilde{B}_{j'n'}(s) \rho_B \right) = \left\langle \widetilde{B}_{jn}(t) \widetilde{B}_{j'n'}(s) \right\rangle_B$ . To evaluate the trace respect to the bath we need to recall that our master equation depends of elements related to the bath and represented by the operators  $\widetilde{B}_{jn}(t)$  and elements related to the system given by  $\widetilde{A}_{jn}(t)$ . The systems considered are in different Hilbert spaces so  $\text{Tr} \left( \widetilde{A}_{jn}(t) \widetilde{B}_{j'n'}(t) \right) = \text{Tr} \left( \widetilde{A}_{jn}(t) \right) \text{Tr} \left( \widetilde{B}_{j'n'}(t) \right)$ . The correlation functions relevant of the master equation (1390) are:

$$\text{Tr}_B \left( \widetilde{B_{jn}}(t) \widetilde{B_{j'n'}}(s) \rho_B \right) = \left\langle \widetilde{B_{jn}}(t) \widetilde{B_{j'n'}}(s) \right\rangle_B \quad (1393)$$

$$= \left\langle \widetilde{B_{jn}}(0) \widetilde{B_{j'n'}}(0) \right\rangle_B \quad (1394)$$

$$= \Lambda_{jnj'n'}(\tau) \quad (1395)$$

$$\text{Tr}_B \left( \widetilde{B_{jn}}(t) \rho_B \widetilde{B_{j'n'}}(s) \right) = \text{Tr}_B \left( \widetilde{B_{j'n'}}(s) \widetilde{B_{jn}}(t) \rho_B \right) \quad (1396)$$

$$= \left\langle \widetilde{B_{j'n'}}(s) \widetilde{B_{jn}}(t) \right\rangle_B \quad (1397)$$

$$= \left\langle \widetilde{B_{j'n'}}(-\tau) \widetilde{B_{jn}}(0) \right\rangle_B \quad (1398)$$

$$= \Lambda_{j'n'jn}(-\tau) \quad (1399)$$

$$\text{Tr}_B \left( \widetilde{B_{j'n'}}(s) \rho_B \widetilde{B_{jn}}(t) \right) = \text{Tr}_B \left( \widetilde{B_{jn}}(t) \widetilde{B_{j'n'}}(s) \rho_B \right) \quad (1400)$$

$$= \left\langle \widetilde{B_{jn}}(t) \widetilde{B_{j'n'}}(s) \right\rangle_B \quad (1401)$$

$$= \left\langle \widetilde{B_{jn}}(\tau) \widetilde{B_{j'n'}}(0) \right\rangle_B \quad (1402)$$

$$= \Lambda_{jnj'n'}(\tau) \quad (1403)$$

$$\text{Tr}_B \left( \rho_B \widetilde{B_{j'n'}}(s) \widetilde{B_{jn}}(t) \right) = \text{Tr}_B \left( \widetilde{B_{j'n'}}(s) \widetilde{B_{jn}}(t) \rho_B \right) \quad (1404)$$

$$= \left\langle \widetilde{B_{j'n'}}(s) \widetilde{B_{jn}}(t) \right\rangle_B \quad (1405)$$

$$= \left\langle \widetilde{B_{j'n'}}(-\tau) \widetilde{B_{jn}}(0) \right\rangle_B \quad (1406)$$

$$= \Lambda_{j'n'jn}(-\tau) \quad (1407)$$

We made use of the cyclic property for the trace to evaluate the correlation functions, from the equations obtained in (1383) and (1390) and using the equations (1393)-(1407) we can re-write:

$$\frac{d\widetilde{\rho_S}(t)}{dt} = - \int_0^t \sum_{j,j',n,n'} \left( C_{jn}(t) C_{j'n'}(s) \left( \Lambda_{jnj'n'}(\tau) \widetilde{A_{jn}}(t) \widetilde{A_{j'n'}}(s) \widetilde{\rho_S}(t) - \Lambda_{j'n'jn}(-\tau) \widetilde{A_{jn}}(t) \widetilde{\rho_S}(t) \widetilde{A_{j'n'}}(s) \right) \right. \quad (1408)$$

$$\left. + C_{jn}(t) C_{j'n'}(s) \left( \Lambda_{j'n'jn}(-\tau) \widetilde{\rho_S}(t) \widetilde{A_{j'n'}}(s) \widetilde{A_{jn}}(t) - \Lambda_{jnj'n'}(\tau) \widetilde{A_{j'n'}}(s) \widetilde{\rho_S}(t) \widetilde{A_{jn}}(t) \right) \right) ds \quad (1409)$$

$$= - \int_0^t \sum_{j,j',n,n'} \left( C_{jn}(t) C_{j'n'}(s) \left( \Lambda_{jnj'n'}(\tau) \left[ \widetilde{A_{jn}}(t), \widetilde{A_{j'n'}}(s) \widetilde{\rho_S}(t) \right] + \Lambda_{j'n'jn}(-\tau) \left[ \widetilde{\rho_S}(t) \widetilde{A_{j'n'}}(s), \widetilde{A_{jn}}(t) \right] \right) \right) \quad (1410)$$

$$\frac{d\widetilde{\rho_S}(t)}{dt} = - \int_0^t \sum_{j,j',n,n'} \left( C_{jn}(t) C_{j'n'}(t-\tau) \left( \Lambda_{jnj'n'}(\tau) [A_{jn}(t), A_{j'n'}(t-\tau, t) \widetilde{\rho_S}(t)] + \Lambda_{j'n'jn}(-\tau) [\widetilde{\rho_S}(t) A_{j'n'}(t-\tau, t), A_{jn}(t)] \right) \right) d\tau - i [H_S(t), \widetilde{\rho_S}(t)] \quad (1411)$$

For this case we used that  $A_{jn}(t-\tau, t) = U(t) U^\dagger(t-\tau) A_{jn}(t) U(t-\tau) U^\dagger(t)$ . This is a non-Markovian equation and if we take  $n = 2$  (two sites),  $\mu_0(t) = 0$ ,  $\mu_1(t) = 1$  then we can reproduce a similar expression to (432) as expected.

## VIII. BIBLIOGRAPHY

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