Distributed Generation Based AC-DC-DC Converter

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Abstract— In this paper a wind turbine Distributed Generation (DG) based AC-DC-DC converter is presented. AC-DC converter is used to supply constant or fixed DC voltage to the DC-DC converter, even in the presence of variations in input or source i.e. wind DG voltage. A new mathematical model has been derived for the above said system consisting DG, AC-DC and DC-DC converter (used for step-up voltage). A novel closed loop transfer function model for AC-DC converter and DC-DC converter is proposed. The control of AC-DC and DC-DC converter is implemented by indirect control strategy and cascaded scheme respectively. Using the derived mathematical model and the above said control, simulation studies have been carried in Matlab/Simulink. The results presented demonstrates excellent performance of overall system in terms of (i) control of voltage at the output of both the converters and (ii) power factor and harmonics at the input or source i.e. DG terminal of the AC-DC-DC converter.

***Index Terms*—Distributed Generation, AC-DC-DC converter**

I. Introduction

Wind turbine generators and solar cells are the renewable energy resources which are being used as Distributed Generation (DG) [1], mainly in the areas where electrical power from the grid is unavailable. Due to the fast depletion of conventional resources, the present trend of electrical power generation is through wind and solar based renewable DG installations. Besides, the advantage of clean or pollution free power generation [2] the major disadvantages of wind based DG are fluctuation in voltage and frequency (of the system), dependency of output power on wind speed, requirement of reactive power (when connected to grid), and regulatory policies [3-5]. Variation in the above said electrical quantities are undesirable in operation, control and protection of a power system and as well as view point of consumer's power quality [6]. Power electronic devices like voltage source converters (rectifiers and inverters) and DC-DC converters, based on the type of DG, have been proposed, in the literature [7-9], to maintain different electrical quantities like voltage, power low, power factor, etc. within the acceptable limits. A Modulated Power Filter Compensator (MPFC) energized by renewable energy based DG is proposed in [10] for improvement of power quality and power factor of a distribution system. However, the scheme requires three loops, one for voltage and the other two for current error and current harmonics. A power electronic based interface consisting of a diode rectifier-intermediate DC boost converter and a voltage fed full bridge converter is proposed in [11] for a wind turbine and super capacitor based hybrid system. Dynamic modeling of a hybrid system consisting of wind-turbine generators, fuel cells and ultra capacitors is presented in [12]. Power generated through wind-turbine is used to supply normal loads. If wind power generation is inadequate, fuel cells supply the excessive power. And, ultra-capacitors are used to supply the load demand (of short-time duration) which is above the load demand supplied by the fuel cells. In [13], a Network-enabled Adaptive Protection and Control (NAPC) strategy for proper interfacing of wind DGs, according to IEEE 1547 interconnection standards, with the distribution grids is presented. Parallel inverters based structure and control to interconnect different type of DG sources like wind-turbine generators, solar cells, fuel cells, etc. for a successful micro-grid operation of a portion of a power system is presented in ref. [14]. The use of a SMES+DSTATCOM system as Distributed Energy Storage (DES) for micro grid operation of power system with wind power generation is presented in [15]. Dynamic security of the system is achieved through stabilization and control of power flow through the tie-lines. Most of the literature, reviewed in this paper, deals with wind DG connected to the grid/system called as grid connected mode of operation and differs completely from the standalone mode in the aspects of voltage, power flow, power quality, etc. due to the absence of link or connection with the power system which acts as source and sink. The goal of this paper is to propose a standalone DG based AC-DC-DC converter, with good power quality i.e. high power factor and very less harmonics in the power system with the proposed converter prevails. Wind turbine generator is considered as a DG source. A new mathematical model for the system consisting of wind DG and AC-DC-DC converter is derived. A new closed loop transfer function model for AC-DC converter, considering indirect control strategy is proposed. AC-DC converter is used to provide constant or fixed DC voltage to the DC-DC converter even in the variation source voltage i.e. DG output voltage due to the variation in wind speed. Whereas, the DC-DC converter is used to supply step-up voltage to the load.

The paper is organized as follows. The impact of variation in wind speed of the wind based DG source on voltage of a power system is presented in Section II. DG based AC-DC and DC-DC (boost) converter are presented in Section III. Based on the models presented in the above section, mathematical model for the proposed DG based AC-DC-DC converter is presented in Section IV. The derivation of new closed loop transfer function model and control of AC-DC converter of the proposed AC-DC-DC converter are presented in Section V. Simulation studies are presented in Section VI and Conclusion of the paper in Section VI.

II. Wind Turbine Generator And Voltage Variation

In this section a brief analysis on power system with wind turbine based DG, shown in Fig. 1, is presented. The aim of analysis is to depict voltage variation due to the variation in active and reactive power flow between the DG and the load. The mechanical power output developed by wind turbine is given by eqn. (1). Where 'ρ' is air density (Kg/m^3), 'C_P' is power coefficient, and 'λ' is tip speed ratio, 'A' is swept area (m^2), and 'v' is wind speed (m/s). The mechanical power output of the wind turbine is 'variable' in nature due to the (natural) changes in wind velocity, air density, etc.

$$P=\frac{1}{2}\rho C_P(\lambda,\beta)Av^3 \tag{1}$$

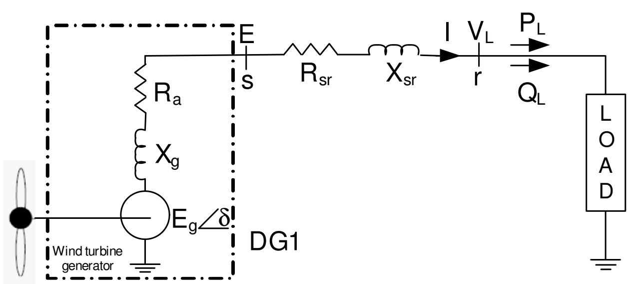

Fig. 1. A simple power system with wind turbine based DG

In Fig. 1, active and reactive power flow between the wind based DG and the grid is variable in nature due to the changes in mechanical power generated. 'DG1' represents a wind turbine generator based DG source. 'E_g' and 'E' are generated and terminal voltage of the DG source respectively. 'V' is called as load bus or receiving end voltage. 'δ' is the angle 'E_g' and 'U'. 'R_a' and 'X_g' represent armature resistance and reactance of the wind generator respectively. 'R_{sr}' and 'X_{sr}' represent resistance and reactance of the line respectively. 'I' is the current flowing from the DG source towards load. 'P_L' and 'Q_L' are active and reactive power drawn by the load through the line.

Voltage at the load and DG terminal is given by eqn. (2) and eqn. (3) respectively [16].

$$V_L = \frac{E_g \text{Cos}\delta + \sqrt{(E_g \text{Cos}\delta)^2 - 4(P_L R_\ell + Q_L X_\ell)}}{2} \tag{2}$$

$$E = \frac{E_g \text{Cos}\delta + \sqrt{(E_g \text{Cos}\delta)^2 - 4(P_L R_a + Q_L X_g)}}{2} \tag{3}$$

Variation in 'E' generator terminal voltage and 'V_L' load voltage with the active and reactive flow are shown in Fig. 2 and Fig. 3 respectively, and are obtained from eqn. (2) and eqn. (3) respectively.

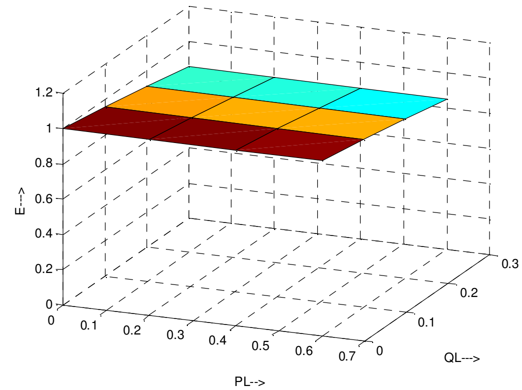

Fig. 2. Voltage at DG1 with variation in reactive and active power

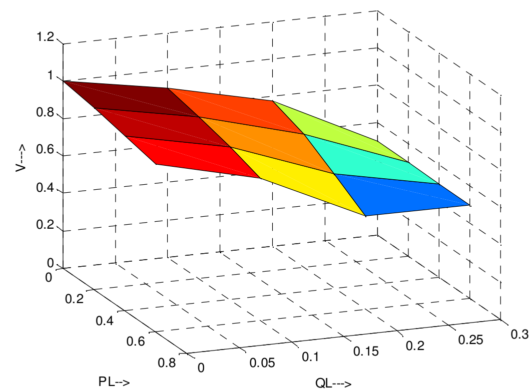

Fig. 3. Voltage at load with variation in reactive and active power

Fig. 2 and Fig. 3 demonstrate that a power system installed with a wind turbine based DG is subjected to voltage fluctuations or variations. The variations in voltage (as well as frequency) should be within the permissible limits for satisfactory operation of the loads connected and can be achieved by using power electronic based converters as presented in Section III and Section IV of the paper.

III. DG based Converters

A. *DG based AC-DC Converter*

DG based AC-DC converter is shown in Fig. 4. Wind turbine generator is considered as a DG source. AC-DC converter converts the AC output voltage (of the wind based DG) to a DC voltage to supply the load. 'v_s' is voltage at the terminal of DG source, and it is fluctuating in nature due to the variation in the wind speed. The load considered here is a resistive load with resistance 'R_L'. The main purpose of AC-DC converter is to supply a constant DC voltage to the load even in the presence of fluctuations in AC voltage of the wind based DG. In Fig. 4, 'i_s' is the current flowing from the DG to converter. 'L_1' is inductance between the DG and converter. 'V_L' is load voltage. 'i_L' is load current. 'K_1V_L' is voltage at the input of the converter, where 'K_1' is the control signal used to produce duty ratio of the converter through Pulse Width Modulation (PWM) techniques. 'C_1' is capacitance connected across the load.

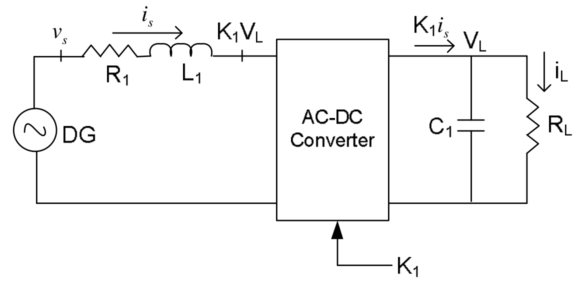

Fig. 4. DG based AC-DC converter

In Fig. 4 applying Kirchhoff's voltage law in the input side of the converter eqn. (4) can be written

$$L_1\frac{di_s}{dt} = v_s - K_1V - i_sR_1 \tag{4}$$

Applying Kirchhoff's current law at the output of the converter eqn. (5) can be written

$$C_1\frac{dV_L}{dt} = K_1i_s - i_L \tag{5}$$

From eqn. (5), it can be said that by controlling 'K_1' load voltage can be regulated. Load voltage can also be maintained at a constant value even in the variation in voltage 'v_s' due to the changes in wind velocity.

B. DC-DC (Boost) Converter

The DC-DC converter considered in this paper is of step-up type and is shown in Fig. 5. The converter is connected to a fixed DC voltage source 'V'. The purpose of the DC-DC converter is to supply DC voltage to the load, after stepping-up from the applied input voltage. In Section V of this paper, the input voltage i.e. 'V' of the converter shown in Fig. 5 is supplied from the AC-DC converter which has been discussed in Section IV.

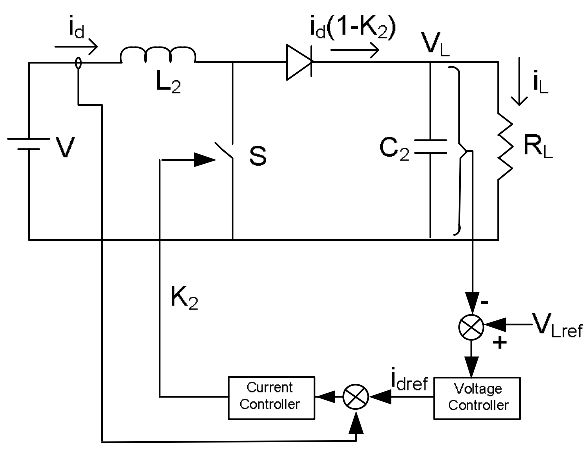

Fig. 5. DC-DC converter

In Fig. 5, dynamics of the current 'i_d' in the inductor 'L_2' and voltage 'V_L' across the capacitor 'C_2' is given by eqn. (6) and eqn. (7) respectively. 'K_2' is the control signal i.e. duty ratio used to control the load voltage.

$$L_2\frac{di_d}{dt} = V - V_L(1-K_2) \tag{6}$$

$$C_2\frac{dV_L}{dt} = i_d(1-K_2) - \frac{V_L}{R_L} \tag{7}$$

From eqn. (7), it can be said by controlling 'K_2' load voltage 'V_L', in Fig. 5, can be regulated to the desired value for which the converter is designed.

IV. DG Based AC-DC-DC Converter

The circuit diagram of the proposed DG based AC-DC-DC converter is shown in Fig. 6. Wind-turbine is considered as a DG source. The output voltage of AC-DC converter is controlled by 'K_1' in order to maintain a fixed or constant input voltage to the DC-DC converter even in the variations of AC output voltage of the wind based DG. The purpose of DC-DC converter is used to supply regulated (step-up) voltage to the load from the fixed DC voltage obtained from the AC-DC converter. The DC-DC converter is controlled by 'K_2'.

In Fig. 6, dynamics of the current flowing from DG source to AC-DC converter is given by eqn. (8); and is rewritten from eqn. (4).

$$L_1\frac{di_s}{dt} = v_s - K_1V - i_sR_1 \tag{8}$$

Dynamics of the capacitor 'C_1' voltage is given by eqn. (9).

$$C_1\frac{dV}{dt} = K_1i_s - i_d \tag{9}$$

The dynamics of current through the inductor 'L_2' and voltage across the load resistance 'R_L' of DC-DC converter is given by eqn. (10) and eqn. (11) respectively.

$$L_2\frac{di_d}{dt} = V - V_L(1-K_2) \tag{10}$$

$$C_2\frac{dV_L}{dt} = i_d(1-K_2) - \frac{V_L}{R_L} \tag{11}$$

Eqn. (8) to eqn. (11) represents non-linear mathematical model of the complete system shown in Fig. 6.

Linearization of eqn. (8) to eqn. (11) gives eqn. (12), linear mathematical model of the system in state variable representation.

$$\begin{bmatrix} \Delta\dot{i}_s \\ \Delta\dot{V} \\ \Delta\dot{i}_d \\ \Delta\dot{V}_L \end{bmatrix} = \begin{bmatrix} -\frac{R_1}{L_1} & -\frac{K_{10}}{L_1} & 0 & 0 \\ \frac{K_{10}}{C_1} & 0 & -\frac{1}{C_1} & 0 \\ 0 & \frac{1}{L_2} & 0 & -\left(\frac{1}{L_2}-\frac{K_{20}}{L_2}\right) \\ 0 & 0 & \left(\frac{1}{C_2}-\frac{K_{20}}{C_2}\right) & \frac{1}{R_LC_2} \end{bmatrix} \begin{bmatrix} \Delta i_s \\ \Delta V \\ \Delta i_d \\ \Delta V_L \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} & -\frac{V_0}{L_1} & 0 \\ 0 & \frac{i_{s0}}{C_1} & 0 \\ 0 & 0 & \frac{V_{L0}}{L_2} \\ 0 & 0 & -\frac{i_{d0}}{C_2} \end{bmatrix} \begin{bmatrix} \Delta v_s \\ \Delta K_1 \\ \Delta K_2 \end{bmatrix} \tag{12}$$

Eqn. (12) reveals that voltage at the output of AC-DC converter (connected to the DC-DC converter) can be maintained constant by the control variable 'K_1', even in the variations of the output voltage i.e. 'v_s' of the DG. Simultaneously, the load voltage across 'R_L' can be regulated to the (designed) desired value by controlling the duty ratio i.e. 'K_2' of the DC-DC converter.

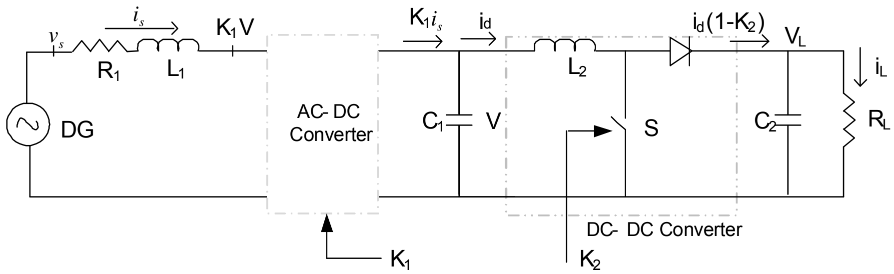

Fig. 6. Proposed wind DG based AC-DC-DC converter

V. Control of Converters

In this section techniques used for the control of AC-DC converter and DC-DC converter are presented.

A. Control of AC-DC Converter

The main function of AC-DC converter is to convert AC supply voltage into DC voltage. AC-DC converter, given in Fig. 4, for load voltage control is shown in Fig. 7. The scheme consists of two cascaded control loops, one for load voltage control and the other for control of source current for power factor correction and harmonic reduction. The voltage control loop and current control loop are called as outer and inner loop respectively. The voltage controller may be a simple Proportional Integral (PI) controller which regulates the DC voltage by controlling the power flow to the DC side. The voltage controller decides required magnitude of AC current 'i_s^*' equivalent to the current on DC side for the current controller. The magnitude of the AC current obtained from the voltage controller is multiplied by a unity magnitude sinusoidal signal of frequency equal to the source voltage and the resultant signal forms the reference current 'i_{sref}' for the current controller. The current controller forces or controls the actual current to take the amplitude and (sinusoidal) waveform of the reference current along with good power factor. It can be said in the cascaded control scheme, shown in Fig. 7, voltage and power factor control at load and source side can be achieved respectively.

The other method of DC-AC converter control for AC to DC conversion is based on indirect current control strategy (also called as sensor less current control) and it is shown in Fig. 8. The objective is to convert AC supply voltage into (regulated) DC voltage by maintaining sinusoidal source current with good power factor. The equivalent circuit diagram of the AC-DC converter (in terms of fundamental components [17]) of the system given in Fig. 8 is shown in Fig. 9. Voltage at the input terminal of the converter is represented by 'v_m' which is the fundamental component (i.e. pure sinusoidal) of the voltage produced at the converter input terminal through PWM technique. The dynamics of the current between the source and the converter is given by eqn. (13). 'v_m' for unity power factor operation of the converter is given by eqn. (14) [17, 18]. It can be observed that the current 'i_s', without any requirement of sensor, can be controlled by controlling 'v_m' and hence the name sensor less current control.

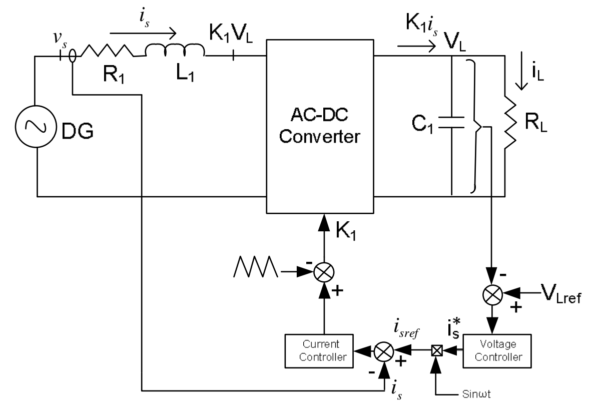

Fig. 7. DG based AC-DC converter with voltage and current controllers

In the above paragraph it has been said by regulating 'v_m', both in magnitude and phase angle, the source current is controlled. The magnitude of current in eqn. (14), which the source current has to follow, is obtained from the voltage controller after processing the dc voltage error signal i.e. V_{Lref}-V_L. In this paper the control of AC-DC converter (of the proposed DG based AC-DC-DC converter), for supplying DC voltage to DC-DC converter, is carried by indirect current control. The advantage of indirect current control strategy scheme is tuning of parameters of only one controller is required.

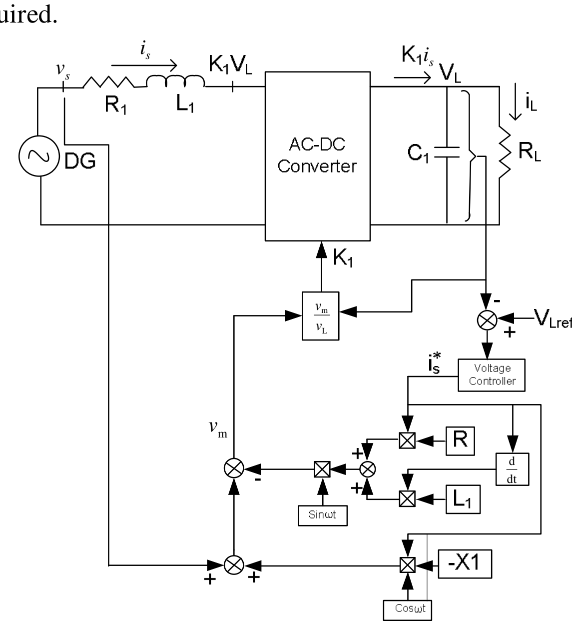

Fig. 8. DG based AC-DC converter with indirect current control

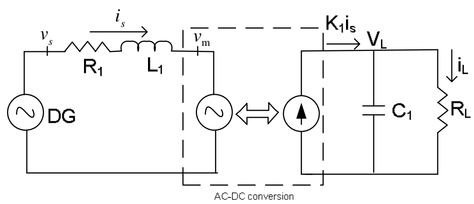

Fig. 9. Equivalent circuit of DG based AC-DC converter

$$\frac{di_s}{dt} = \frac{v_s - v_m - i_s R_1}{L_1} \tag{13}$$

$$v_m = \left(V_s - R_1 i_s^* - L_1 \frac{di_s^*}{dt} \right) \sin \omega t - X_1 i_s^* \cos \omega t \tag{14}$$

B. Proposed Transfer Function Model of the AC-DC Converter System-Indirect Current Control Strategy

The main objective of the AC-DC converter is to perform AC to DC conversion, and there should be no deviation of source current from (i) sinusoidal wave form and (ii) the source voltage in terms of phase (for unity power factor operation) for a satisfactory performance of the overall system. From eqn. (13), neglecting source voltage 'v_s', transfer function of inductor circuit for the circuit shown in Fig. 9 is given by eqn. (15).

$$\frac{i_s(s)}{v_m(s)} = \frac{1}{sL_1 + R_1} \tag{15}$$

Considering the right hand side portion of the circuit shown in Fig. 9 and substitution of $i_L = V_L/R_L$ in eqn. (5) gives the transfer function of capacitor as given by eqn. (16).

$$\frac{V_L(s)}{K_1 i_s(s)} = \frac{R_L}{sR_L C_1 + 1} \tag{16}$$

Neglecting source voltage 'v_s' and taking the Laplace transform of eqn. (14) transfer function between 'v_m' and 'i_s^*' can be obtained and is given by (17).

$$\frac{v_m(s)}{i_s^*(s)} = \frac{-2X_1 s - R_1 \omega}{s^2 + \omega^2} \tag{17}$$

It is said earlier that the voltage controller is used to process the dc voltage error signal i.e. V_{Lref}-V_L. Transfer function of the voltage controller used in Fig. 8 is given by eqn. (18). Where, $E(s)=V_{Lref}-V_L$.

$$\frac{i_s^*(s)}{E(s)} = \frac{sK_p + K_i}{s} \tag{18}$$

From eqn. (15) to eqn. (18) the proposed closed loop transfer function model of the AC-DC converter system (based on indirect control strategy) consisting AC-DC converter, PWM (module) and a PI controller (for DC voltage control) is given by eqn. (19) and the closed loop control block diagram is shown in Fig. 10.

$$\frac{V_L(s)}{V_{Lref}(s)} = \frac{n_1 s^2 + n_2 s + n_3}{b_1 s^5 + b_2 s^4 + (b_1\omega^2 + b_3)s^3 + (b_2\omega^2 + n_1)s^2 + (b_3\omega^2 + n_2)s + n_3} \tag{19}$$

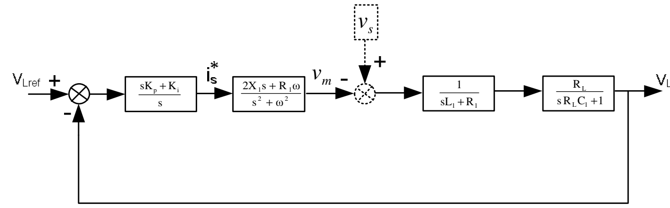

Fig. 10. Control block diagram of AC-DC converter based on the proposed closed loop transfer function model

C. Control of DC-DC Converter

The mathematical model considered for DC-DC (boost) converter, shown in Fig. 5, is given by eqn. (20) and eqn. (21) respectively.

$$L_2 \Delta \dot{i}_d = (K_{20} - 1)\Delta V_L + V_{Lo}\Delta K_2 + \Delta V \tag{20}$$

$$C_2 \Delta \dot{V}_L = (1 - K_{20})\Delta i_d - i_{do}\Delta K_2 - \frac{\Delta V_L}{R_L} \tag{21}$$

The control of converter consists of a voltage and (inductor) current controller connected in cascade. The actual voltage i.e. 'V_L' across the load is compared with the set or reference voltage i.e. 'V_{Lref}'. The voltage error is processed by the voltage controller and the reference or set point for the inductor current is produced. The actual inductor current 'i_d' is compared with the reference inductor current 'i_{dref}' and the error generated is processed by the current controller to produce the duty cycle 'K_2' such that the actual voltage and actual inductor current follows the reference voltage and reference inductor current respectively.

VI. Simulation Results

Simulation studies on the proposed wind DG based AC-DC-DC converter, shown in Fig. 6, have been carried in MATLAB/SIMULINK. Numerical values of the parameters of the system are given in Table 1.

Table. 1. Parameters of the system shown in Fig. 6

Parameter	Value
V_s	141V
R_1	0.8Ω
L_1	5mh
C_1	200µF
V_L	400V
V	200V
L_2	10mh
C_2	2500µF
R_L	390Ω

The response of output voltage of DC-DC converter for reference input voltage of 310 V is shown in Fig. 11 and the waveform of inductor current in Fig. 12. It can be seen from Fig. 13 that the input to DC-DC converter is maintained at 200 V by the AC-DC converter even under the variation in source voltage as shown in Fig. 14. It can be observed, variation in source voltage due to the variation in wind speed is 25 percent. From Fig. 14, it can also be observed that the source current is nearly sinusoidal and power factor is unity.

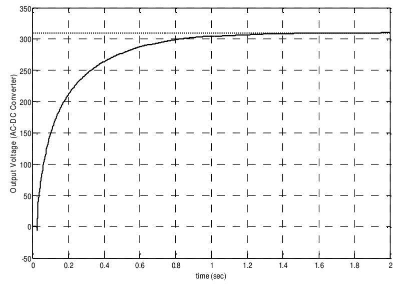

Fig. 11. Output voltage of the DC-DC converter for a constant reference voltage of 300 V and with variation in wind speed of the DG.

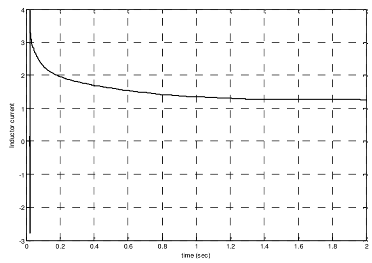

Fig. 12. Inductor current of DC-DC converter when the load voltage is maintained at 310V.

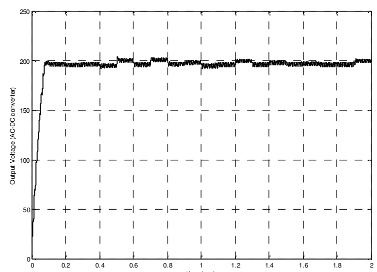

Fig. 13. Output voltage of the AC-DC converter (connected to DG with variation in wind speed) maintained at 200V when the output voltage of the DC-DC converter is at 310 V.

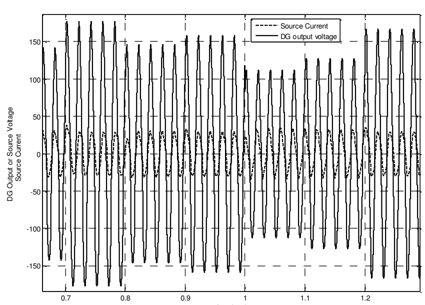

Fig. 14. Output voltage and current of the DG with variation in wind speed and the load voltage maintained at 310V.

VII. Conclusion

A wind turbine Distributed Generation (DG) based AC-DC-DC converter is presented. The converter comprises of AC-DC converter connected to a step-up DC-DC converter. AC-DC converter is used to provide constant or fixed DC voltage to the DC-DC converter, irrespective of variations in input or source i.e. wind DG voltage to which it is connected. The contributions of this paper are derivation of a new (i) mathematical model for wind DG fed AC-DC-DC converter considering DG, AC-DC and DC-DC converter on a single-plat form and (ii) closed loop transfer function model for AC-DC converter. The control of AC-DC and DC-DC converter of the DG based AC-DC-DC converter is implemented by indirect control strategy and cascaded scheme respectively. It has been shown through simulation studies, in Matlab/Simulink, that the performance of overall system is excellent in terms of voltage at the output of both the converters and power factor and harmonics at the input of the AC-DC-DC converter.

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