Predictive Control of Power Electronics Autotransformer for Mitigating Three-Phase Grid Current Unbalance in Railway Supply Systems

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Keywords

≪Railway power supply≫, ≪Power quality≫, ≪Current balancing≫, ≪Converter control ≫, ≪Grid-connected converter≫.

Abstract

In order to mitigate the unbalance of three-phase grid currents that is commonly prevalent in single-phase railway supply lines, a predictively controlled power electronics autotransformer is proposed in this paper. It comprises of a pair of back to back single-phase voltage source converters that are strategically connected between different phases of the three-phase grid. Using finite control set model predictive control, the converters are intelligently controlled with a regulated DC link, to draw balanced sinusoidal three-phase grid currents at nearly unity input power factor, even as the rail system connects as a single-phase load on the three-phase network. This in turn helps in maintaining the balance and quality of three-phase voltage supply at the point of common coupling.

Introduction

High speed railway traction systems typically use a 25 kV single-phase (1-ϕ) power supply that is generated through a step down transformer connected across two phases of a 132 kV three-phase (3-ϕ) transmission grid. This is popularly achieved through a 2×25 kV split-phase (± 25 kV AC) arrangement, which is well proven to provide better efficiency [1]. Such a system is illustrated in Fig.1, where the overhead train line is at +25 kV (AC) with respect to the running rails, while there is a parellel negative feeder at -25 kV (AC). Regularly spaced auto-transformers connected between the split-phase network, continuously divert the returning rail currents along the negative feeder. Although the 2×25 kV railway supply system is widely prevalent world-over, it has significant drawbacks such as reactive power consumption and unequal loading of the three-phase grid [2]. An undesirable consequence of unbalanced grid currents is the deterioration in 3-ϕ voltage balance at the point of common coupling, which in turn has adverse effects on other end-user equipments connected to the same network [3].

A number of solutions have been proposed to maintain balanced 3-ϕ grid currents in 1-ϕ railway supply systems. These include passive solutions [4] as well as active solutions like rail power flow controllers [5, 6, 7]. This paper proposes an alternative 3×25 kV supply system coupled with a power electronics auto-transformer (PEAT), to mitigate grid current (and hence grid voltage) unbalance in railway power networks. The proposed system replaces the single-phase split-arrangement supply with a three-phase

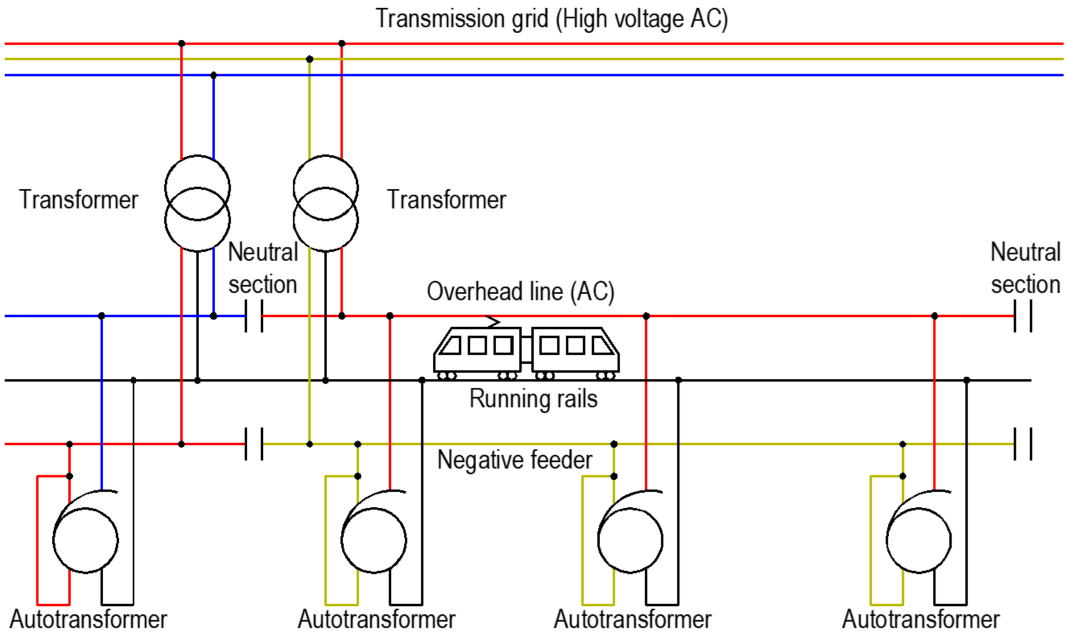

Fig. 1: Conventional state of the art 2×25kV railway power supply system with regularly spaced autotransformers

transformer, which is cost-effective, compact and more efficient. While the rail load is supplied between two phases of the 3-ϕ transformer output, the compensating power electronics autotransformer (PEAT), comprising of back to back 1-ϕ voltage source converters (VSCs), is connected between different phase-pairs on its either end. The PEAT circuit is strategically operated to compensate for the single-phase train load on the three-phase network, ensuring balanced 3-ϕ power withdrawal from the grid, while circulating only a fraction of the total power. The circuit diagram of the proposed railway power supply and the PEAT connections are demonstrated in Fig.2.

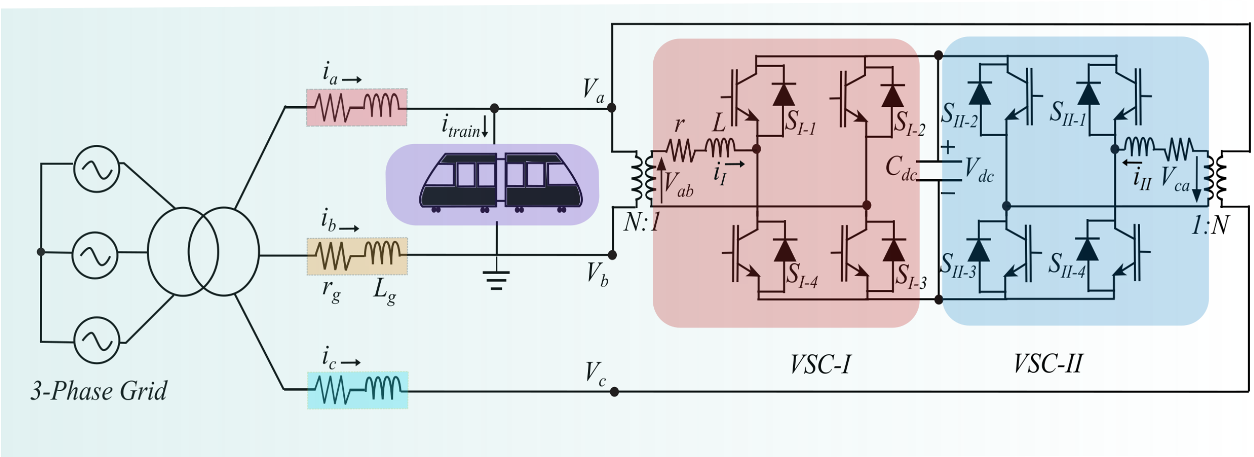

Fig. 2: Proposed 3×25kV railway power supply system with power electronics autotransformer

Control of Power Electronics Autotransformer

The back to back VSC pair forming the PEAT circuit is controlled to regulate the DC link voltage, compensate for the reactive component of source currents and to maintain balanced three-phase grid currents. In order to ensure fast and precise control of the power electronics auto-transformer, predictive current control is independently exercised for regulating the input currents of each VSC. Besides facilitating fast control dynamics with easy inclusion of system non-linearities, the use of predictive control also ensures that all objectives are accomplished with minimal sensing requirements, as the controlled currents are not measured, but mathematically predicted [8]. Due to these attractive features, predictive control is gaining rapid popularity in the control of power converters for various applications, including rail converters [9]. The reference currents for VSC-I and VSC-II, i.e i_I^* and i_{II}^* are generated as per various control objectives, followed by implementation of predictive current control for each VSC.

Reference Current Generation for PEAT

The first voltage source converter VSC-I, connected between the same phase pairs as the rail load, is controlled to ensure reactive power compensation, and to maintain the DC link voltage. On the contrary, VSC-II is responsible for drawing power balanced current in the otherwise unconnected phase of the 3-ϕ grid. Together, both converters work in tandem to maintain balanced 3-ϕ source currents.

For the control of VSC-I, the reference d-component of converter current (i_{Id}^*) is generated to regulate the DC link voltage, and the reference q-component of converter current (i_{Iq}^*) is derived to minimize the reactive component of the source currents. This is mathematically given as,

$$\begin{aligned} i_{Id}^* &= \left(k_p^d + \frac{k_i^d}{s}\right)\left(V_{dc}^* - V_{dc}^f\right) \\ i_{Iq}^* &= \left(k_p^q + \frac{k_i^q}{s}\right)\left(i_q^* - (N \times i_q)\right) \end{aligned} \tag{1}$$

where, V_{dc}^* is the reference DC link voltage, V_{dc}^f is the measured DC link voltage after digital filtering, i_q^* is the reference q-component of source currents which is ideally set to zero, and i_q is the actual q-component of the source currents (i_{abc}). It must be noted that i_q is derived by using the phase angle from three-phase grid voltage to ensure reactive power minimization. Further noteworthy to mention is that the source currents (i_{abc}) are not directly measured, but estimated through measurement of train current and prediction of converter currents i_I and i_{II}. The use of predictive control significantly minimizes sensing requirements for undertaking current control.

From the dq components i_{Id}^* and i_{Iq}^*, the reference current i_I^* for VSC-I is generated as,

$$i_I^* = i_{Id}^* \, sin(\theta_{ab}) + i_{Iq}^* \, cos(\theta_{ab}) \tag{2}$$

where,θ_{ab} is the continuos phase of the converter side voltage, V_{ab}, obtained through a single-phase second order generalized integrator (SOGI) based phase locked loop.

For the control of VSC-II, the reference converter current (i_{II}^*) is derived from power balancing, followed by alignment with voltage of the unconnected phase (C) and subsequent reflection to the low voltage secondary (converter) side of the interfacing transformer. This is given as,

$$i_{II}^* = \left[\left(\frac{V_a.i_a + V_b.i_b + V_c.i_c}{V_a^2 + V_b^2 + V_c^2}\right) \times V_c\right] N \tag{3}$$

Once the reference currents i_I^* and i_{II}^* for VSC-I and VSC-II are produced, predictive current control of the converters is undertaken such that the VSCs are switched to draw currents as per their reference values.

Predictive Current Control

Finite set model predictive control (FS-MPC) is undertaken for VSC-I and VSC-II, to ensure that each converter traces its reference input current independently. The converter input currents, i_I and i_{II} are predicted one sample time ahead for all switching states of VSC-I and VSC-II, respectively. Switching models of the converters and discretized mathematical models of the interfacing inductors are used in generating the current predictions. The governing equations for VSC-I and VSC-II are respectively given as,

$$
\begin{aligned}
V_{ab} &= i_I r + L\frac{di_I}{dt} + [S_{I\text{-}1} + S_{I\text{-}3} - S_{I\text{-}2} - S_{I\text{-}4}]\frac{V_{dc}}{2} \\
V_{ca} &= i_{II} r + L\frac{di_{II}}{dt} + [S_{II\text{-}1} + S_{II\text{-}3} - S_{II\text{-}2} - S_{II\text{-}4}]\frac{V_{dc}}{2}
\end{aligned} \tag{4}
$$

Upon discretization, the converter currents for the j^{th} switching state in the $(k+1)^{th}$ sample time, are predicted for VSC-I and VSC-II respectively. These predictions are given as,

$$
\begin{aligned}
i^j_{I(k+1)} &= \frac{V_{ab} - i_{I(k)}r - [S^j_{I\text{-}1} + S^j_{I\text{-}3} - S^j_{I\text{-}2} - S^j_{I\text{-}4}]\frac{V_{dc}}{2}}{L} T_s + i_{I(k)} \\
i^j_{II(k+1)} &= \frac{V_{ca} - i_{II(k)}r - [S^j_{II\text{-}1} + S^j_{II\text{-}3} - S^j_{II\text{-}2} - S^j_{II\text{-}4}]\frac{V_{dc}}{2}}{L} T_s + i_{II(k)}
\end{aligned} \tag{5}
$$

These current predictions are made for all four switching states of each converter and the corresponding errors in converter currents with respect to their reference signals are computed for each state. The errors for j^{th} state, for VSC-I and VSC-II are respectively given as,

$$
\begin{aligned}
e^j_I &= [i^*_I - i^j_{I(k+1)}]^2 \\
e^j_{II} &= [i^*_{II} - i^j_{II(k+1)}]^2
\end{aligned} \tag{6}
$$

Independently for each converter, the switching state that yields the least error is finally switched in real time. It must be noted, that the control algorithm eliminates converter current measurement by propagating ahead the current prediction of the winning state, each time a switching decision is made.

Simulation Results

In order to ascertain the performance of power electronics autotransformer in mitigating 3-ϕ grid current unbalance in 1-ϕ railway supply systems, the proposed control algorithm is validated through simulation and analysis in Matlab/Simulink environment. The simulations are conducted for a 25 kV three-phase supply, with the 1-ϕ railway line connected between two of the three phases and a PEAT circuit connected across different phase pairs. Various system parameters used in the simulation are enlisted in Table-I.

Table I: Simulation Parameters

Parameter	*Value*
3-ϕ Secondary Side Supply Voltage	$25kV$ $(L-L)$, $50Hz$
Grid Impedance $(L_g),(r_g)$	$10mH, 2\Omega$
Filter Parameters $(L),(r)$	$8mH, 0.5\Omega$
Transformer turns ratio $(N:1)$	$27.78:1$
DC Link Capacitance (C_{dc})	$8000\mu F$
DC Link Voltage (V_{dc})	$3000V$
Rail Load Emulating Resistance	$400\Omega/200\Omega$
Maximum Traction Power	$3.125MW$
Prediction Horizon/Sample Time (T_s)	$10\ \mu s$

The compensating performance of PEAT is well illustrated in Fig.3. The 3-ϕ source currents (i_{abc}), and their positive ($i_{abc}\ ^{(+)}$), negative ($i_{abc}\ ^{(-)}$), and zero sequence ($i_{abc}\ ^{(o)}$) components, respectively are shown in Fig.3(a). At t=2.5 s, the PEAT circuit is disconnected to demonstrate unbalanced grid currents that are otherwise drawn by 1-ϕ railway lines. An unwelcome consequence of unbalanced grid currents, is the deterioration of voltage balance at the point of common coupling (PCC). To depict the promising impact of PEAT circuit, the PCC voltage (V_{abc}) and its sequence components, with and without the PEAT circuit are shown in Fig.3(b).

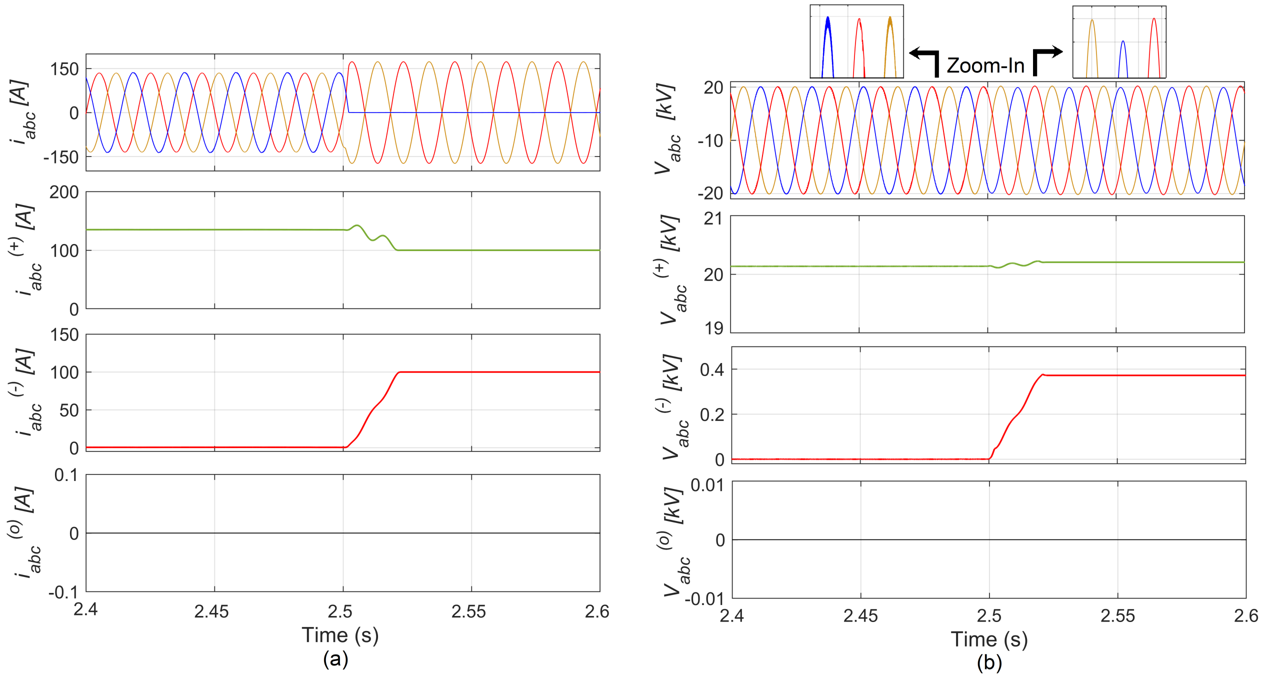

Fig. 3: System operation with and without power electronics autotransformer; (a) Three-phase source currents and their sequence components (b) Three-phase voltages at the point of common coupling and their sequence components

The dynamic response of the PEAT circuit with respect to an abrupt increase in the train load at t=3 s, is demonstrated in Fig.4. Fig.4(a) shows the 3-ϕ source currents (i_{abc}) and the sequence components of PCC voltage (V_{abc}), while Fig.4(b) shows the tracking performance of DC link voltage and converter currents i_I and i_{II} as the train load is abruptly increased. The DC link voltage reference is uniformly maintained at 3000 V.

The power quality performance of the proposed system is demonstrated in Fig.5. Fig.5(a) shows the source current (i_a) at nearly unity input power factor with respect to PCC voltage, V_a. Fig.5(b) shows the harmonic spectrum of grid current with a total harmonic distortion of only 0.58 %, which is well within the norms of IEEE-Std 519. It is well known that finite state model predictive control is a variable switching frequency algorithm, hence resulting in sporadic harmonic spectra.

Conclusion

From the aforementioned discussion, results and analysis, it is concluded that a 3×25 kV railway supply system when augmented with a power electronics autotransformer, can serve as a demonstrable alternative to conventional 2×25 kV railway supplies with passive autotransformers. While handling fractional power, the PEAT circuit can be effectively controlled to ensure that the 1-ϕ railway line appears as a balanced 3-ϕ load on the grid, with minimal harmonics and reactive power control.

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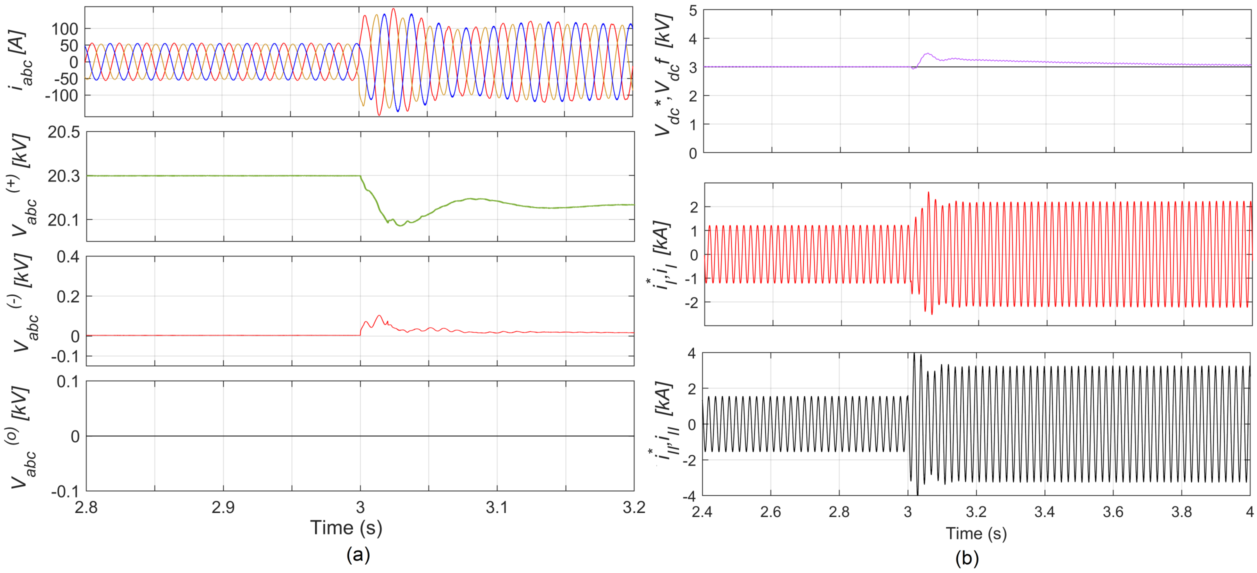

Fig. 4: Dynamic response of power electronics autotransformer during abrupt change in rail load; (a) Three-phase source currents (i_{abc}) and sequence components of voltage at the point of common coupling (V_{abc}). (b) Tracking response of DC link voltage (V_{dc}), and converter currents i_I and i_{II}.

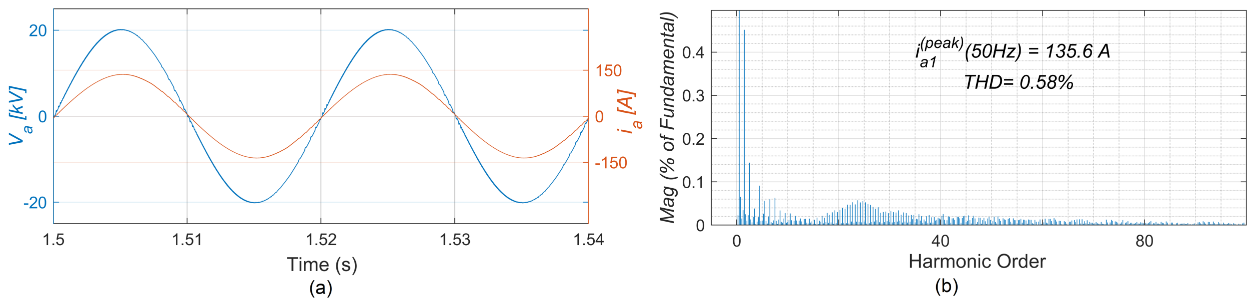

Fig. 5: Power quality performance of the power electronics autotransformer; (a) Source current (i_a) at nearly unity power factor with respect to voltage, V_a. (b) Harmonic spectrum of source current (i_a).

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