Power Quality Improvement of DC Electrified Railway Distribution Systems Using Hybrid Filters

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Abstract—**DC Electrified railways play an important role for metropolitan public transportation because of high efficiency, heavy ridership and fast transportation. However, the electrified railways cause great problems for the power quality of the distribution system feeding the traction system such as injecting harmonics, reactive power compensation and low power factor issue. These problems can be solved by using a hybrid filter in the traction substations. In this paper, a modified PQ control system has been applied for the control of shunt active filter, while the passive filters are used for reducing most of the severe harmonics. The simulation is done with PSCAD/EMTDC proving the efficiency of the proposed hybrid filter structure for reducing the current harmonics, voltage and current balancing, reactive power compensation and power factor improvement.**

I. INTRODUCTION

Application of DC electrified railways as a significant metropolitan means of transportation is increasing greatly. DC Electrified railways play an important role for public transportation because of high efficiency, heavy ridership and fast transportation. However, they result in great power quality problems for the power distribution system which feeds the traction system. In DC electrified railways, the rectifiers of the traction substations are a major cause of harmonic distortion in the AC supply. High THD of the system current, harmonics and interharmonics, reactive power consumption, voltage unbalance and flicker and low power factor problems can suffer the power distribution system feeding the traction system greatly [1-4].

In anticipation of the proliferation of nonlinear loads and to limit the problems, recommended guidelines like the IEEE-Std 519-1992 specify the allowable harmonic associated in the currents drawn from the utility system. Different methods are utilized for improving the power quality issues of the power distribution system such as dynamic voltage regulators, statcoms and active or hybrid filters.

In this paper, a hybrid filter structure with a new and simple control technique is used for power quality improvement of the distribution system feeding the DC electrified railway systems. Studying and comparing the simulation results carried out with PSCAD/EMTDC software prove that the proposed method can effectively eliminate harmonic currents, balance source currents, compensate reactive power and correct power factor of the power system, in other words, power quality improvement of the power system is achieved by the proposed hybrid filter structure and control method.

II. POWER SUPPLY SYSTEM DESCRIPTION

The power distribution system of DC electrified railways include traction substations for stepping down and converting the AC voltage to DC and also lightning substations for each station. The schematic diagram of the power distribution system of a DC electrified railway is shown in Fig. 1.

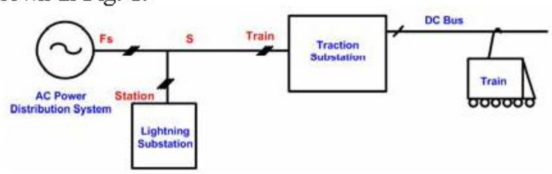

Fig. 1. Schematic of the power distribution system of DC electrified railways.

The traction substation has one or two 20 kV /0.592 kV/ 0.592 kV three winding transformers with Y/Y/Δ connections which step downs the 20 kV AC grid voltage to 592 volts AC. Two six-pulse rectifier units are connected in parallel to the outputs of the transformer which convert the 592 volts AC to 750 volts DC. Therefore, a 12 pulse rectifier is utilized in the traction substation for reducing the amount of harmonics in the system. The DC voltage is then transmitted along the track through overhead contact or third rail systems. The schematic diagram of the traction substations is shown in Fig. 2. The lighting substation that is used to consumption of lighting, ventilation and lifts in the stations utilize a 20 kV/400 V transformer with Y/Δ connection.

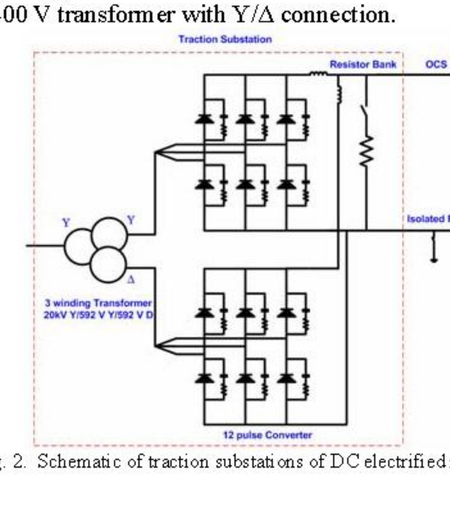

Fig. 2. Schematic of traction substations of DC electrified railway.

For studying the load flow analysis of the traction power distribution systems, the power consumption of the train operation is necessary to be investigated and the dynamical behavior of the traction system loads along the route to be studied. Fig. 3 shows the typical speed profile of a train set between two stations which consists of acceleration, constant speed and braking periods [10]. When train is in the brake mode, the regenerative energy will be converted back into the DC line that can provide a part of the required power for the other running trains along the track.

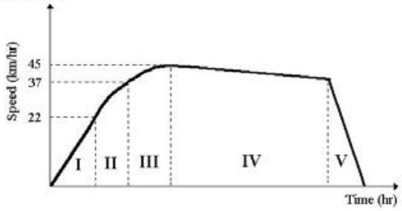

Fig. 3. Speed characteristics of the train sets with time variations.

III. Power Improvement Filter Structure

A. Passive Filters

Passive filters as classic methods for power quality improvement of distribution systems consist of series LC tuned for removing a specific harmonic or blocking a bandwich of severe harmonics of nonlinear loads current. These filters have low impedances for the tuned frequencies such as 5th and 7th and for these frequencies, the lower impedance of the filter in comparison with system impedance, the better filtering characteristics of the passive filter. Low cost is a great benefit of these filters but because of their LC constant parameters, they cannot be efficient power quality improvement facilities for dynamic nonlinear loads. Another problem of installation of passive filters is probable resonances between the impedance of passive filter and the system resulting in increasing the harmonics of system current.

B. Active Filters

Active filters as modern applications of power electronic inverters are used to fulfill the necessity of compensating the harmonics of power systems for dynamic conditions such as switching on and off loads and DG units. Shunt active filters are used at main bus of distribution systems for reducing the amount of current harmonics of the system being inserted to HV network. These filters are controlled as current sources for producing non-sinusoidal currents according to non-sinusoidal current of loads or system for removing the harmonics and making system current sinusoidal. These filters suffer from high ratings that increase the cost of project.

C. Hybrid Filters

Hybrid filters constructed of active and passive filters with different structures are used for removing the disadvantages of passive filters such as probability of resonances and non dynamic responses and also high costs of active filters, while using the advantage of both of the filters with lower costs. Different structures of hybrid filters can be utilized in power systems such as shunt passive filter and series active power filter with nonlinear loads, shunt active and passive filter with nonlinear load, series active and passive filter parallel with nonlinear load, etc. as shown in Fig. 1.

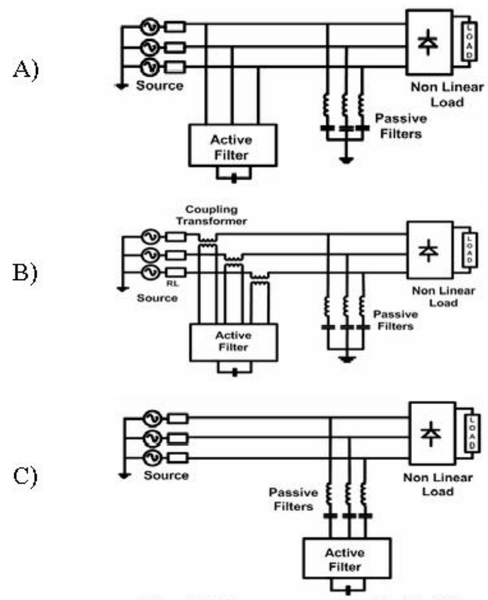

Fig. 4. Different structures of hybrid filters.

D. Hybrid Filter Topology

Active power filter is widely used in distribution power networks to improve the power quality where the purpose of using shunt active power filter is to cancel the load current harmonics fed into the power supply. It can also contribute to reactive power compensation and balancing of three-phase currents. In an active power filter, a controller determines the harmonics that are to be eliminated and also the reactive power that is to be compensated. The output of this controller is the reference of a three-phase current controlled inverter. Fig. 5 illustrates the schematic diagram of the statcom structure and connections used in the DC traction substation.

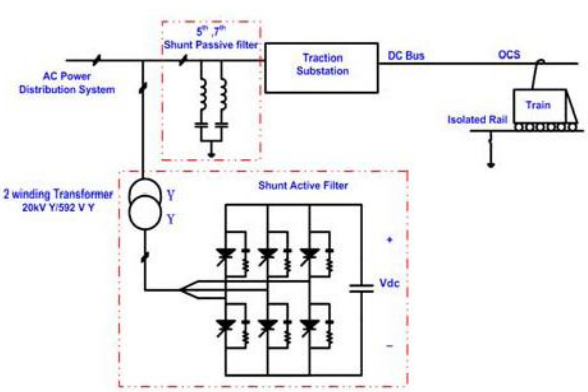

Fig. 5. Schematic diagram of the statcom for DC electrified railways.

In this paper, a Modified PQ reference current calculation method is used for controlling the active filter where the compensating reference currents are as follows:

$$\begin{bmatrix} i_{f\alpha} \\ i_{f\beta} \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} v_{\alpha} & -v_{\beta} \\ v_{\beta} & v_{\alpha} \end{bmatrix}\begin{bmatrix} P_{L(os)} \\ Q_{L} \end{bmatrix} \quad (1)$$

$$\Delta = v_{\alpha}^{2} + v_{\beta}^{2} \quad (2)$$

Utilizing a PI controller for keeping the DC voltage bus to a constant value, the output of controller is multiplied by capacitor current to calculate Pc losses. This power is added to the compensated active power, and then the compensating reference currents are calculated as:

$$\begin{bmatrix} i_{f\alpha} \\ i_{f\beta} \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} v_{\alpha} & -v_{\beta} \\ v_{\beta} & v_{\alpha} \end{bmatrix}\begin{bmatrix} P_{L(os)} + Pc \\ Q_{L} \end{bmatrix} \quad (3)$$

The hysteresis current control is applied to the modified PQ compensation method for PWM controlling of the switchings of the inverter.

IV. Simulation Results

The simulation is done with PSCAD/EMTDC software where a DC electrified railway system is simulated as described in section 2. the simulation is done for the system without any filters, with usage of just 5th and 7th shunt passive filters, with usage of just a shunt active filter and with usage of the hybrid filter structure proposed in section 3.

The Current waveforms of the distribution system feeding DC electrified railway without any filters are shown in Fig. 6. The low power factor of the system can also be studied through the difference between the voltage and current waveforms of the system as shown in Fig. 7. The active and high reactive power consumption of this system is also shown in Fig. 8. The current harmonic spectrum of the system shown in Fig. 9, proves the system of high THD and harmonic contents.

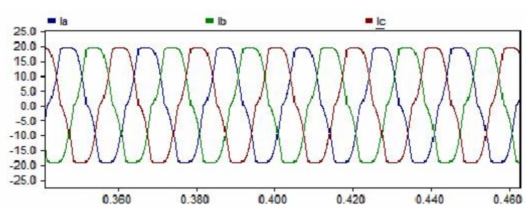

Fig. 6. Current waveforms of the distribution system feeding DC electrified railway without any filters.

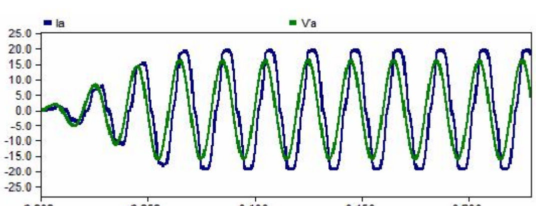

Fig. 7. Voltage-Current waveform of the distribution system feeding DC electrified railway without any filters.

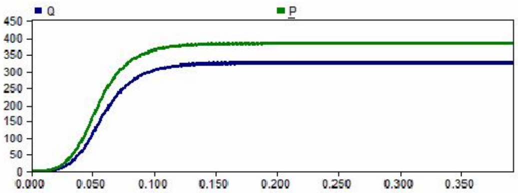

Fig. 8. Active and reactive power waveforms of the distribution system feeding a DC electrified railway without any filters.

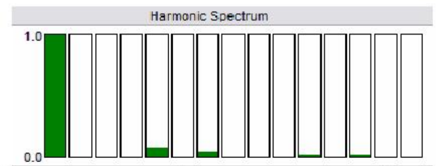

Fig. 9. Harmonic spectrum of the current waveform of the distribution system feeding DC electrified railway without any filters.

Using 5th and 7th shunt passive filters can greatly reduce the harmonic contents and compensate the reactive power but with lower performance at the load changes. The Current waveforms, power factor, active and reactive power consumption of the system and current harmonic spectrum for the distribution system feeding the DC electrified railway are shown in Figures 10-13 where the passive filters are switched on at 0.5 s.

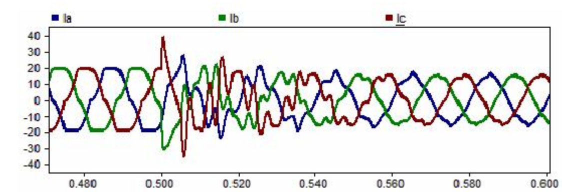

Fig. 10. Current waveforms of the distribution system feeding DC electrified railway using passive filters.

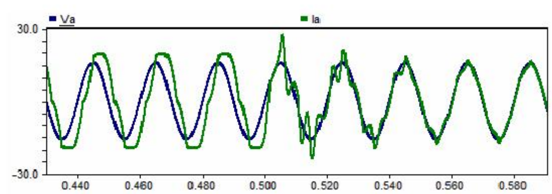

Fig. 11. Voltage-Current waveform of the distribution system feeding DC electrified railway using passive filters.

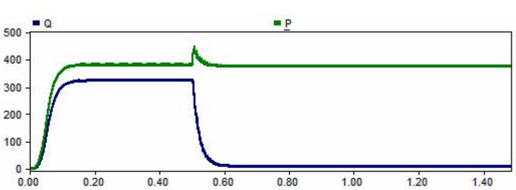

Fig. 12. Active and reactive power waveforms of the distribution system feeding a DC electrified railway using passive filters.

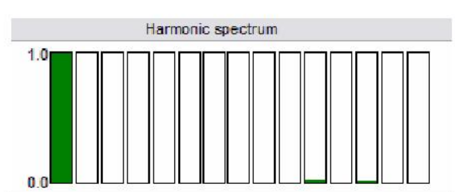

Fig. 13. Harmonic spectrum of the current waveform of the distribution system feeding DC electrified railway using passive filters.

Using a shunt active filter also reduces the harmonic contents and compensates the reactive power but for higher costs. The Current waveforms, power factor, active and reactive power consumption of the system and current harmonic spectrum for the distribution system feeding the DC electrified railway are shown in Figures 14-18 where the active filter is switched on at 0.555 s. It is obvious that the active filter can start compensation at dynamic situations much faster than passive filters. Fig. 17 also shows the active power consumption of the bare shunt active filter structure.

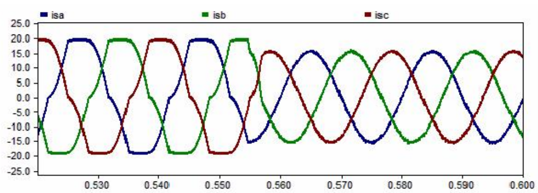

Fig. 14. Current waveforms of the distribution system feeding DC electrified railway using shunt active filter.

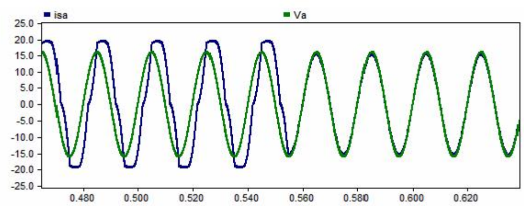

Fig. 15. Voltage-Current waveform of the distribution system feeding DC electrified railway using shunt active filter.

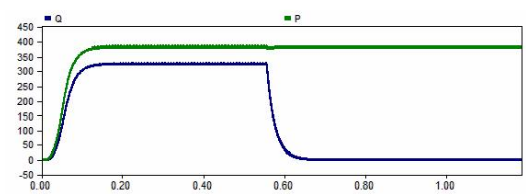

Fig. 16. Active and reactive power waveforms of the distribution system feeding a DC electrified railway using shunt active filter.

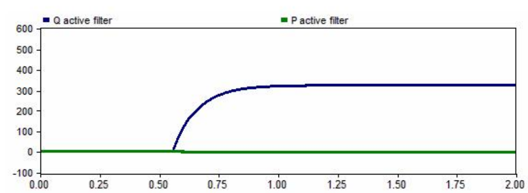

Fig. 17. Active and reactive power consumption of the active filter while using only a shunt active filter.

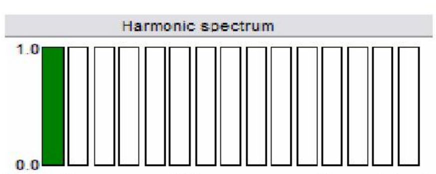

Fig. 18. Harmonic spectrum of the current waveform of the distribution system feeding DC electrified railway using active filter.

Using the proposed hybrid filter structure consisting of a shunt active power filter and 5th and 7th shunt passive filters has the best performance in harmonic reduction, power factor improvement and reactive power compensation with lower active power consumption, lower costs and higher capabilities at dynamic situations as shown in Figures 19-23.

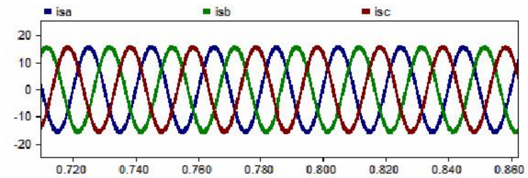

Fig. 19. Current waveforms of the distribution system feeding DC electrified railway using hybrid filters.

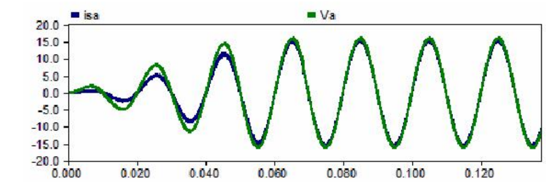

Fig. 20. Voltage-Current waveform of the distribution system feeding DC electrified railway using hybrid filter.

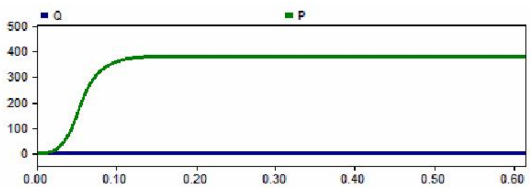

Fig. 21. Active and reactive power waveforms of the distribution system feeding a DC electrified railway using hybrid filter.

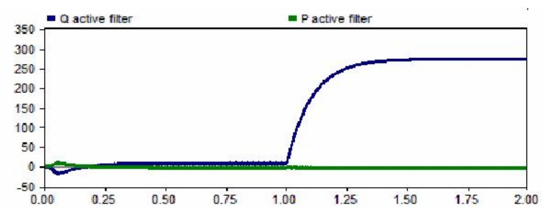

Fig. 22. Active and reactive power consumption of the active filter while using hybrid filter.

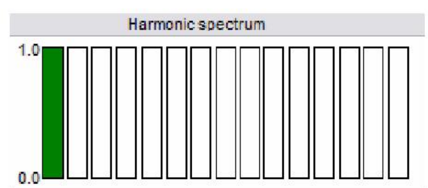

Fig. 23. Harmonic spectrum of the current waveform of the distribution system feeding DC electrified railway using hybrid filter.

Comparing the results of current THD and harmonic contents through the simulation for the system without any filters, with usage of just 5th and 7th shunt passive filters, with usage of just a shunt active filter and the hybrid filter structure proposed in this paper, prove the efficiency of the proposed hybrid filter structure in current harmonic reduction as shown in Table I.

TABLE I
THD AND HARMONIC CONTENTS OF THE CURRENT OF THE POWER SYSTEM FEEDING DC RAILWAYS WITH DIFFERENT FILTER STRUCTURES

System and Filter Configurations	THD%	h_5	h_7
Without any filters	8.3	0.0763	0.0281
With only 5^{th} & 7^{th} Shunt Passive Filter	2.27	0.0031	0.0031
With only Shunt Active Filter	0.34	0.0021	0.0024
With Hybrid Filter (AF+PFs)	0.11	0.0011	0.0010

V. CONCLUSION

In this paper a hybrid filter constructed of a shunt active filter and passive filters are utilized for power quality improvement of the distribution system feeding DC traction systems. The simulation is done with PSCAD/EMTDC for the system without any filters, with usage of just 5^{th} and 7^{th} shunt passive filters, with usage of just a shunt active filter and the hybrid filter structure proposed in this paper. The results of the simulation prove the efficiency of the hybrid filter structure in current harmonic reduction, reactive power compensation and power factor improvement with less cost and technical problems.

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