A Novel Control Scheme of the Statcom for Power Quality Improvement in Electrified Railways

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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 issues of the power distribution system feeding the traction system such as injecting harmonics, reactive power compensation and low power factor issue. The problem can be solved by adding a statcom to the traction substations. In this paper, a novel control system has been applied for the control of statcom, comparing its efficiency and characteristics with the mostly used PQ method. The simulation is done with PSCAD/EMTDC proving the efficiency of the control system 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 problems for the power distribution system which feeds the traction system in power quality issues such as injecting harmonics, reactive power compensation and low power factor issue. 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].

Different methods are utilized for improving the power quality issues of the power distribution system such as active or hybrid filters, dynamic voltage regulators and statcoms. In this paper, a statcom is applied for the traction substation which behaves as a shunt active filter when the train is consuming power from the network to compensate reactive power and harmonics [5-7], and behaves as an inverter which converts the regenerative energy back into the AC power grid also when the train is in brake mode.

Different methods are used for controlling the switchings of statcoms [8-9] but in this paper, a new control scheme is applied to the statcom which enables the reactive power compensation and harmonic reduction in the case of system unbalanced voltage. The results of the simulation done with PSCAD/EMTDC software prove the efficiency of the utilized statcom topology and its control scheme for improving the power qualities of the AC power distribution system.

II. POWER SUPPLY DESCRIPTION

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

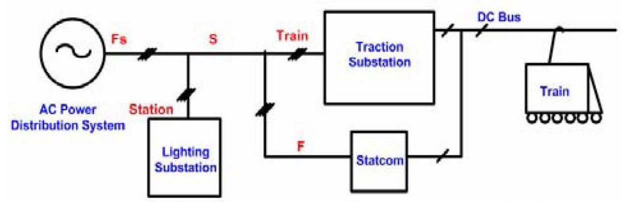

Fig. 1: Schematic diagram of the power distribution system feeding a DC electrified railway system

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, 1500 or 3000 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.

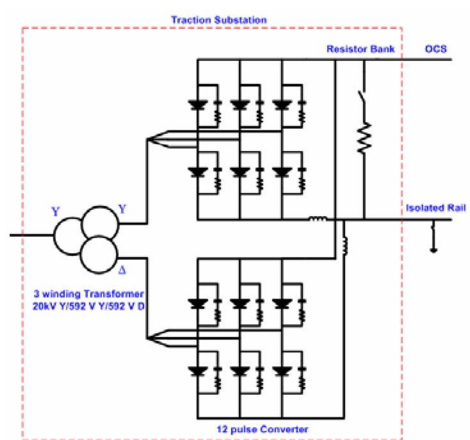

Fig. 2: Single Line diagram of the traction substations for DC electrified railway

In this paper, a train set of a 750 volts DC railway system is simulated with PSCAD/EMTDC software which uses series extinction DC motors as its tractive force production with regenerative braking ability. The train set is a 3-car set and there are four DC motors on each of the car used for generating the sufficient traction force for the train set.

III. DYNAMIC TRAIN LOAD

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 [10]. When the train starts from the first station, it operates in constant acceleration mode, shown in region I. As the speed reaches 22 km/hour, the operation mode is changed to constant power, shown in region II. When the speed is above 37 km/hour, the train set is operated with the constant slip where the traction effort is inversely proportional to the square of the train speed, shown in region III. After the speed reaches the cruising speed, the train operates with coasting mode without applying any input propulsion power, shown in region IV. When the train approaches the next station, the electric regeneration braking is applied by operating the induction motors as induction generators so that the kinetic energy of the train set can be converted into electricity to achieve the energy conservation, shown in region V. For each operation mode, the power demand of the train set can be solved based on the acceleration and various types of train resistance. The track layout including route gradient and curvatures of the traction system, the distance between the adjacent stations and also the headway time of the trains for different traffic and service schedules have also a great effect on the dynamic load behavior of the traction systems.

When train is in the brake mode, the regenerative energy will be converted back into the AC power grid that can provide a part of the required power for the other running train sets on the track or the lighting substations, which its amplitude depends on the regenerative DC current.

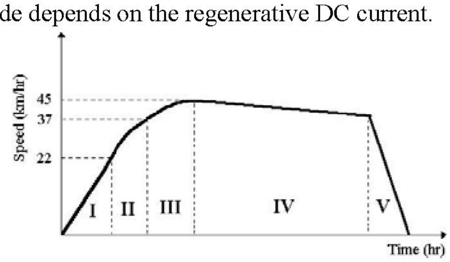

Fig. 3: Speed characteristics of the train sets with time and place variations

IV. STATCOM TOPOLOGY

Power electronics appliances are used widely in industrial, commercial and consumer environment. These appliances generate harmonic and reactive current in the utility system that cause EMI pollution to other loads in the system. 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. 4 illustrates the schematic diagram of the statcom structure and connections used in the DC traction substation.

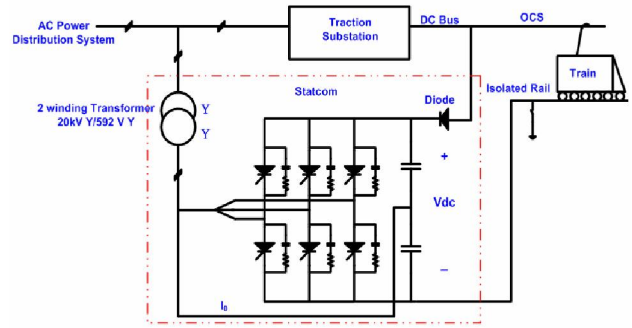

Fig. 4: Single line diagram of the statcom application for DC electrified railway systems

Different methods are used for calculating the reference currents of the active filter such as Synchronous reference frame method, PQ method, Modified PQ method and Instantaneous active and reactive current component method. In this paper, a new reference current calculation method is used for controlling the active filter which has been compared with the results of using modified PQ method.

The compensating reference currents with modified PQ method 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 for this modified PQ compensation method for PWM controlling of the switchings of the inverter.

The new control method is based on the principle of balancing the current waveforms of the AC power network, preventing its distorting and in phasing it with the positive sequence of the source voltage, even if the source voltage is unbalanced and is distorted because of harmonics. Therefore minimum average active power consumption of the active power filter, harmonic current compensation, neutral current compensation, reactive power compensation and unity power factor are the goals of using such a control system [11].

The main components of the new control system for the statcom are the reference compensation current calculator, switch controller and a DC voltage controller. The reference compensation current calculator includes a phase locked loop, a peak voltage detector and a sine wave generator. The switch controller also includes a voltage source PWM controlled inverter and a hysteresis band current controller.
The schematic diagram of the new control method of the statcom is shown in Fig. 5.

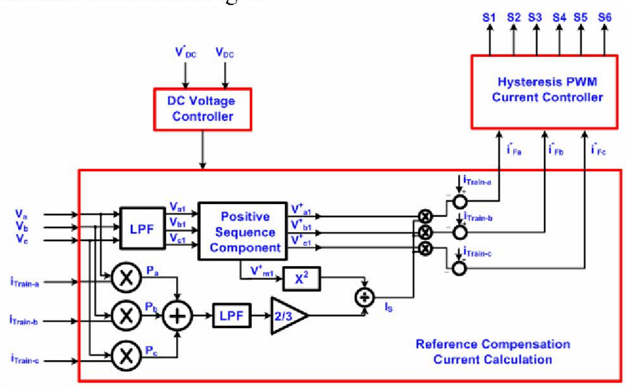

Fig. 5: Schematic diagram of the new control system for the Statcom

V. SIMULATION RESULTS

The simulation results are carried out by PSCAD/EMTDC software. Without using the statcom, when train is in regenerative braking mode, the energy is dissipated in the resistor banks; therefore, the current of the overheard contact system is zero at that time as shown in Fig. 6. The reactive and active power consumption of the traction system is also shown in Fig. 7. Fig. 8 shows the harmonic current and voltage waveforms of the AC power network feeding the traction system.

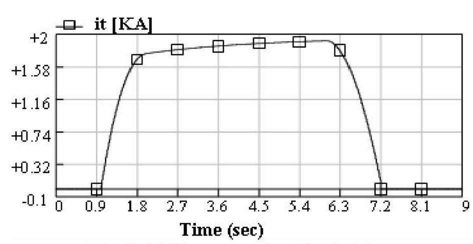

Fig. 6: DC bus current without statcom

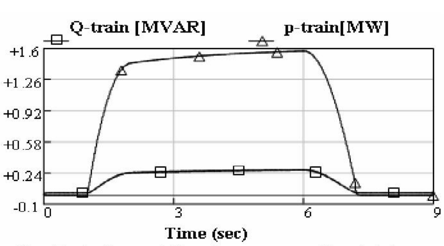

Fig. 7: Active and Reactive power without statcom

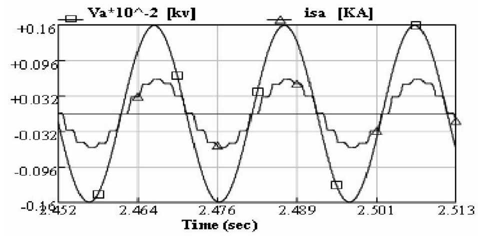

Fig. 8: Power supply current and voltage without statcom

In this paper, the regenerative energy are converted back into the AC network utilizing the statcom. The diode which is connected between the DC bus and the statcom is used for defining the regenerative braking mode of the DC motors. The DC current waveform is given in Fig. 9 and the current passing through the diode is shown in Fig. 10 , which is equal to the regenerative current.

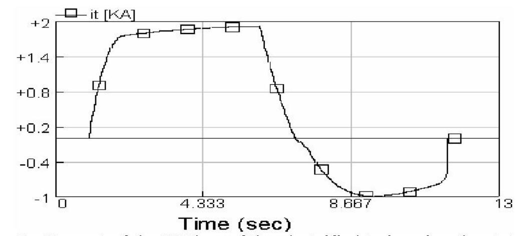

Fig. 9: Current of the DC bus of the electrified train using the statcom

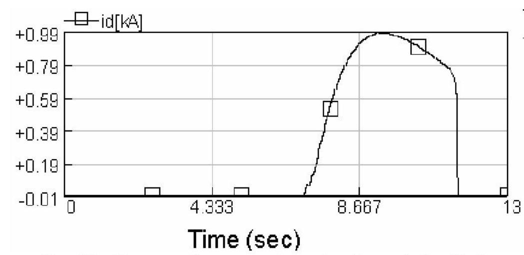

Fig. 10: Regenerative current passing through the diode

For proving the efficiency of the new control system of the statcom in comparison with PQ control method, a highly distorted and unbalanced voltage has been applied to the the AC power network. Fig. 11. shows the system unbalanced and distorted voltage and Fig.12. shows the currents of AC power network before the application of statcom to the system.

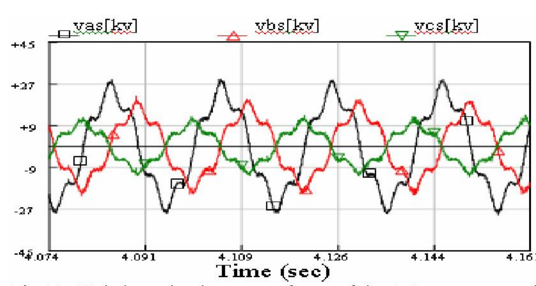

Fig.11: Unbalanced voltage waveforms of the AC power network

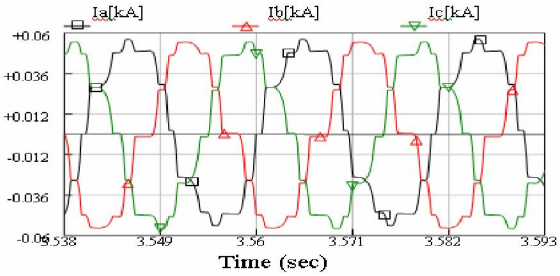

Fig.12: Harmonic currents waveforms of the AC power network feeding the traction substation before compensation

Utilizing a statcom with PQ control method, the current waveforms of the AC power network are not compensated completely, but applying the new control method, the current waveform is completely compensated, regardless of the source voltage condition. The waveforms of the compensated current with PQ and new control methods are shown in Figures 13 and 14, respectively.

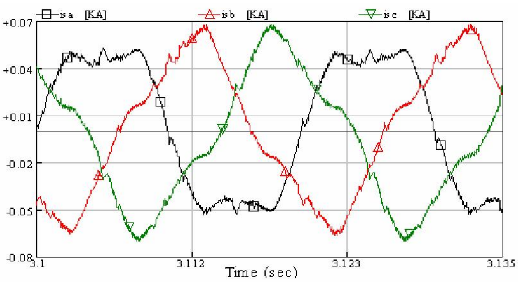

Fig. 13: Currents waveforms of the AC power network feeding the traction substation utilizing a statcom with PQ control method

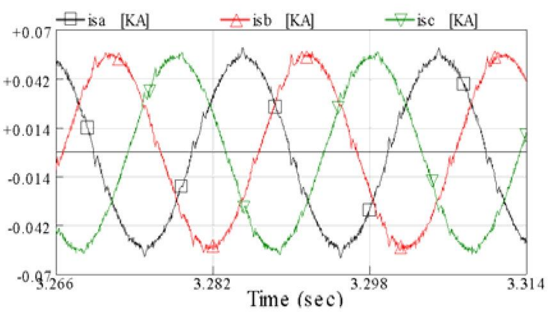

Fig. 14: Currents waveforms of the AC power network feeding the traction substation utilizing a statcom with the new control method

As shown in Fig. 1, assuming the active and reactive powers of the train (p-train, q-train), active and reactive powers of the statcom (pf, qf), the connecting point of statcom (pf, qf) and the connection point of the statcom to the AC power network (Ps, Qs), the active and reactive powers for the study case utilizing a statcom with PQ and the new control method are shown in Figures 15 and 16. Studying these figures, it is obvious that when the train is in the regenerative braking mode, q-train is zero and qf is equal to qs. This means that regenerative energy is converted back in to the AC network Figures 17 and 18 also show the active and reactive powers of Main station (p-fs, q-fs), Lighting station (p-station, q-station) and connecting point of statcom and train (ps, qs) with statcom. When train is in brake mode, the regenerative energy is transmitted back into the Lighting substation for providing its power consumption.

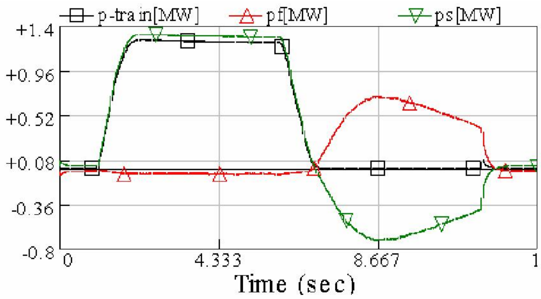

Fig. 15: Active powers of Train (p-train), Statcom (pf) and the connecting point of the statcom (ps) for two control schemes of PQ and the new method

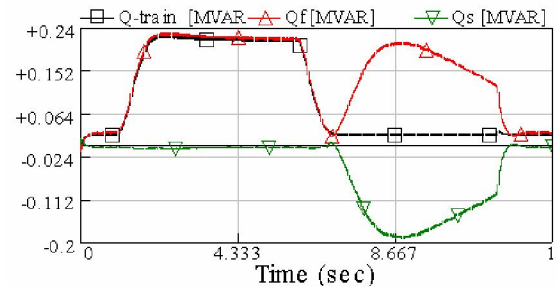

Fig. 16: Reactive powers of Train (q-train), Statcom (qf) and the connecting point of the statcom and train (qs) for two control schemes of PQ and the new method

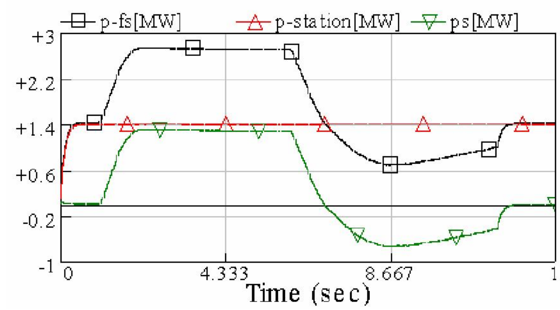

Fig. 17: Active power of Main station (p-fs), Lighting station (p-station) and the connection point of the statcom (ps) for two control schemes of PQ and the new method

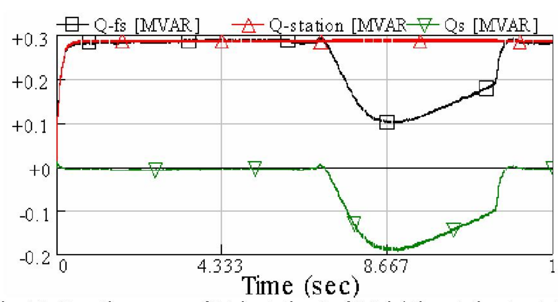

Fig. 18: Reactive power of Main station (q-fs), Lighting station (q-station) and the connection point of the statcom (qs) for two control schemes of PQ and the new method

VI. CONCLUSION

In this paper a statcom with a new control scheme was applied for power quality improvement of the power distribution system feeding a DC electrified railway system. The proposed statcom can be considered as an active filter to compensate reactive power and harmonics and also as an inverter to covert the regenerative energy back into the AC grid, when the train is in regenerative brake mode. The proposed method is able to reduce the current harmonics and compensate reactive power and improve the power factor of the system even if the supply voltage is in distorted and unbalanced.

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