Super Conducting Fault Current Limiter Based Railway Power Conditioner for Electric Traction System

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Abstract: The effective operation of high speed locomotives depends upon the certain characteristics such as power factor, harmonics and supply voltage. The major problems in electric locomotives are low power factor, high harmonics and voltage unbalance due to fault currents. There are many methods used to improve the above characteristics such as FACTS (Flexible AC Transmission System) devices. But, they cannot adjust dynamically and also it is not cost effective. In addition the load characteristics of electric traction changes with respect to time. Subsequently, the unbalanced load creates an unbalanced voltage in transmission lines. Unbalancing voltage in the source affects the equipment, reduces the power generation capacity and further reduces the transmission line output. In present days, many controllers such as APF(Active Power Filter), PI(Proportional Integral) and FACTS devices are used to control electric power. Fault currents creates voltage unbalance in transmission line. In this paper, RPC (Railway Power Conditioner), along with PID (Proportional Integral Derivative) and SFCL (Superconducting Fault Current Limiter) is proposed to improve the power factor and to reduce harmonics and unbalance voltage due to current faults. RPC is efficient in improving power quality. Power factor can be improved by PID controller. If a fault occurs in a transmission line, fault current is decreased by SFCL. After fault clearance, voltage unbalance created by railway 1-phase traction loads can rapidly be decreased. As a result, electric railway system and transmission returns to steady state. Specifically, SFCL has an advantage of speedy operation as it balances the voltage within ¼cycle. The proposed method and technology is tested on MATLAB/SIMULINK environment.

Keywords: RPC (Railway Power Conditioner), PID (Proportional Integral Derivative), SFCL (Superconducting Fault Current Limiter).

I. INTRODUCTION

Electric traction is utilized to diminish the utilization of fossil fuels, decrease carbon discharge, to meet the load demand and performance improvement. Railway power systems need to be expanded and operate more effectively due to increased transport demands on rail [1]. In present days, electric railway system is rapidly developed. However, there are major problems in high-speed electric locomotive loads, such also w power factor, harmonics, current faults, voltage unbalance [2]. To reduce this problem, huge amount of negative sequence currents are injected into the traction transmission line [3], negative sequence currents causes disturbances in traction system, vibration and additional loss occurs in DC series motor, it may create an effect on transformer. RPC is more efficient in negative sequence compensation. To solve the power quality issue, power factor has to be improved [3], [4], and [5]. Also, it is necessary to reduce the negative sequence currents. “Following are the methods used to inject negative sequence currents into the traction system: • Connecting unbalanced load to different supply terminals. [3] • Adopting phase sequence rotation to make unbalanced load distributed to each sequence reasonably. [5] • Connecting unbalanced load to higher voltage level supply terminals. • Using balanced transformers such as Scott transformer and impedance balance transformer. [4]

In addition, this electric traction system uses a single phase source supplied through a transformer from three phase transmission system, which has rapidly changing load characteristics in time. These characteristics can cause a fault and voltage unbalance in transmission line.” As technology increases, there are many methods to be used to improve the power factor, to reduce voltage unbalances and fault currents. FACTS devices are used in present days to control power flow in transmission system and to maintain voltage stability. The FACTS devices, such as APF(Active Power Filter), Static Compensator (STATCOM) have become focus on power quality compensation of electric traction system [5], [6], and [7]. All the FACTS devices need high voltage transformers which may increase the cost of the system. Compare to all FACTS devices, APF is more effective in reducing harmonic currents in traction system [8]. The rest of this paper is organized as follows. Section II details an analysis and compensation of three station RPC(Railway Power Conditioner). In section III, Steinmetz Theory. In section IV, SFCL modeling. Section V, method for improving the
II. ANALYSIS AND COMPENSATION OF THREE STATION RPC AND VOLTAGE UNBALANCE IN TRACTION SYSTEM

A. Analysis of Three Station RPC With PID

In Reference Paper [9], the author has explained how to make the 5-6 locomotive loads from unbalanced condition to balanced condition, with the help of PI controller. The power factor of electric locomotive must be closer to one. In this paper, to improve the power factor, unbalancing voltage and current faults in the transmission line a new device of three station RPC with PID (Proportional Integral Derivative) and SFCL (Superconducting Fault Current Limiter) technique is used to operate the circuit breaker at unbalanced condition to balanced condition at 0.2sec, 0.3sec, 0.5sec. Fig.1 shows the structure of three station RPC. The power supplied from generating station is 220kV. Three phase 220kV voltage is stepped down to two single phase power supply voltage in to range of 27.5kV by V-V transformer, connected one line to another line to the tracks of electric railway traction. RPC (Railway Power Conditioner), RPC1, RPC2, RPC3 are made up of IGBT, with diode connected back-to-back voltage source converters and a common dc capacitor, which can provide a dc-link stable voltage.

Two converters are connected to secondary arms of V-V transformer by step down transformer. One converter can supply active power, another converter can supply reactive power and can compress harmonic currents in the transmission line. From one RPC1, right feeder section in Fig.1 is denoted as a-phase power arm connected from Phase-A conductor. Similarly the left side is b-phase power arm connected from Phase b connected. Fundamental current vector of a-phase power arm, I_{aL}, and the fundamental current vector of Phase-b power arm, I_{bL} are given below: [9], [10]

\[
I_{aL} = I_{aL} e^{-j30^\circ} \\
I_{bL} = I_{bL} e^{-j90^\circ} \\
I_A = I_{aL} - \frac{I_{aL}}{K} e^{-j30^\circ} \\
I_B = I_{bL} - \frac{I_{bL}}{K} e^{-j90^\circ} \\
I_C = -( I_A + I_B )
\]

The turn’s ratio of V-V transformer is K, so the three currents of the high voltage side are given as: [9], [10]

\[
\dot{I}_A = \frac{I_{aL}}{K} e^{-j30^\circ} \\
\dot{I}_B = \frac{I_{bL}}{K} e^{-j90^\circ} \\
\dot{I}_C = -( I_A + I_B )
\]

Before the Three Station RPC Compensation, a-phase power arm has load current I_{aL} and b-phase power arm has load current I_{bL} so that the phase currents I_{AL} \geq I_{BL}. We arrange the Circuit Breaker to compensate the locomotive load from unbalanced condition to balanced condition. [9]

![Fig.1. Simulation Diagram of Three Station RPC Compensation with SFCL.](image)

The three phase current is unbalance before compensation as shown in Fig.2. Using RPC to shift \( \frac{1}{2}(I_{bL}-I_{aL}) \) from a-phase to b-phase. Then, the current of two power arms are compensated to \( I_{aL} \) and \( I_{bL} \), and they have an equal amplitude of \( \frac{1}{2}(I_{aL}+I_{bL}) \) and an angle difference of \( \pi/3 \). The unbalance level is 50% now. By injecting negative sequence currents to both sides of the transformer with the help of DC capacitor we can get the locomotive loads from unbalanced condition to balanced condition as shown in Fig.3. A-phase currents is \( I_{acq} \) and similarly B-phase currents is \( I_{bcq} \) [9].

\[
I_{acq} = \frac{1}{2}(I_{aL} + I_{bL}) \tan 30^\circ \\
I_{bcq} = \frac{1}{2}(I_{aL} + I_{bL}) \tan 30^\circ
\]
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International Journal of Advanced Technology and Innovative Research
Volume.08, IssueNo.02, February-2016, Pages: 0245-0251

Fig.3. Three-phase current phase diagram after adjusting active and reactive power by RPC.

B. Simulation of Three Station RPC Control By PID Controller

Fig.4 shows the Control block diagram of 3 Station RPC. When the traction is at unbalanced condition output 1 & 2 are connected to add. The error value is of two outputs is added, the error value is to make product to either in SIN terms or COSINE terms, it depends upon the error value with the help of the controller.

Fig.4. Control Block Diagram of the Three Station RPC.

Electric railway traction system widely adopts the single phase sequence rotation in power supply system. Three station RPC compensation is mainly discussed in this paper. Fig.4 shows the simulation diagram of three station control by PID controller. The capacity in phases AB, BC and CA is x, y, z, which has a relationship of x>y>z. The network of AB, BC and CD can be divided into two parts, one network is used to balance the railway power supply Z, the other network is used to unbalance the railway power supply at conduction x-z, y-z, 0. Here X=x-y, Y=y-z, Z=0, the original network is simplified as 0, YX.

Set X/2 as the reference value, the P.U. value of the simplified network is 2, Y', 0. Y' is varying from 0 to 2. The extreme case is Y'=0. The simple model of 3 stations structure is shown in Fig.5. Since RPC could transfer a quantity of active power and compensate reactive power, a triangle is applied to illustrate the principle of collaboration compensation, apexes of the triangle are regarded as active load in Phase-AC, Phase-BC and Phase-AB, and edges of the triangle are regarded as three RPCs. The arrows mean the delivery of active power (real part) and compensation of reactive power (imaginary part). There are three steps to compensate. Firstly, transfer a quantity of active power. Secondly, separate the network into two parts: a balanced network and an unbalanced network. And last, make compensation to the unbalanced network based on the Steinmetz theory.

Fig.5. The simple model of 3 stations structure.

III. STEINMETZ THEORY

According to the Steinmetz theory, in Reference [9] and [15] values of a and b are taken as 1/3 and we make the breaker to operate at 0.5sec. In this paper, the breaker is operated at 0.2sec, 0.3sec, 0.5sec. The fully compensation
should satisfy the relationship of $b + c = \frac{2-3a}{\sqrt{3}}$. The capacity of RPC1, RPC2 and RPC3 are $\sqrt{a^2 + b^2}$, $\sqrt{a^2 + c^2}$ and $c$ respectively. The installed capacity will be the maximum of three RPC capacities above. So we can obtain the minimum installed capacity when $a = \frac{1}{\sqrt{3}}$ and $b = \frac{1}{\sqrt{3}}$, and the minimum capacity is $S_{\text{min}} = \frac{1}{\sqrt{3}} + \frac{1}{\sqrt{3}} = c$. This is a fully compensation but the station where RPC2 installed is capacitive. To avoid this condition, RPC1 supply inductive reactive power with the value of $b$, and RPC2 supply capacitive reactive power with the value of $b$, too. So the capacitive condition is avoided and the system keeps balance at the same time.

$$ Z(t) = \begin{cases} 0 & (t < t_0) \\ Z_n \left[ 1 - \exp \left( \frac{t-t_0}{\tau_2} \right) \right]^\frac{1}{2} & (t_0 \leq t < t_1) \\ a_1(t - t_1) + b_1 & (t_1 \leq t < t_2) \\ a_2(t - t_2) + b_2 & (t \geq t_2) \end{cases} $$

(8)

Where $Z_n$ and $T_f$ are the impedance saturated normal temperature and time constant. In addition, $t_0$, $t_1$, and $t_2$ are the quench-starting time, first recovery-starting time, and second recovery-starting time respectively. $a_1, a_2, b_1$ and $b_2$ are coefficients of the first-order linear function to denote the experimental results of the recovery characteristics of the SFCL [11]. The recovery time of the SFCL is set to the value until fault clearing to protect the transmission line.

Fault Modelling of the Transmission line in the Electric Railway. Generally, an electric railway is connected to a 220 kV transmission line through transformer. Fig.1 shows a transmission system connected with railway equivalent model. FACTS devices are installed to control power flow in transmission line, and an electric railway includes a single phase load that causes a voltage unbalance in transmission line. Here, in order to analyze the fault of an electric railway in transmission line, we simulated a fault simulation. Fig.3 shows the fault location on the transmission line. Fault starting time is 0.1s and fault duration is 0.5s. Fig. 3 Shows simulation results for a three-phase fault for an electric railway connection, respectively. In case of fault on a transmission line, after fault removal three phase voltage is deceased there is a transient phenomenon that has a small offset voltage but returned to a steady state. In addition, this simulation showed a small magnitude difference between offset voltages. Current is generated a large transient current during fault and reach to steady state, load current, after fault removal. In addition, voltage unbalances of transmission line became more serious in transmission line. Line currents also increased and caused unbalance to transient voltage. These phenomenon will cause problem about voltage stability and malfunction of protection scheme in the transmission grid. These results show that an electric railway connection increases voltage unbalance in the transmission line.

### A. Unbalanced Load in an Electric Railway System

An electric railway traction system characteristic that most utilities are concerned with this current unbalanced produced by large single phase loads [10], [11]. These unbalanced currents cause three-phase voltage unbalance in a system. To minimize voltage unbalance in three-phase power feed networks, Scott transformers are widely used. Unbalance loads can change single-phase loads. If a line fault occurs in a transmission line voltage unbalance is produced in the system."[12]

### IV. MODELING THE SFCL AND FAULT OF THE TRANSMISSION LINE IN AN ELECTRIC RAILWAY

#### A. Resistor-Type SFCL Modelling

In order to limit a fault current, many models have been developed for SFCL resistor-type, reactor type, transformer type, etc.[13]. In this study, we modeled a resistor-type SFCL that is mostly basic and used widely which represents the experimental studies for superconducting elements of SFCL. Quench characteristics and recovery characteristics of a resistor-type SFCL are modeled based on [13] and [14]. An impedance of the SFCL at time $t$ is given as:
particular, SFCL has advantage of fast operation within ¼ cycle [12]. In SFCL operating process, after clearing the fault, improving the voltage unbalance within ¼ cycle is showed in fig.4 (a) and 4(b). “The operation characteristics of conventional relay and breaker are greater than 5-15 cycles. As mentioned in the fault modeling, a single phase load in an electric railway is one of the cause of voltage unbalance in the transmission system. However, the proposed method using SFCL can alleviate this problem. SFCL was installed in the transmission line between the source and electric railway system, in case study simulation using the MATLAB software SFCL decreases the voltage unbalance, fault current, harmonics. Fig.1 shows the transmission system including an electric railway and fig.3 shows the results when SFCL is operated. The result shows the fault current limiting characteristics and improving voltage unbalance. In addition, SFCL has following features: 1) the larger resistance of resistor type SFCL, the more voltage unbalance was improved. 2) If a fault occurs, the proposed method clears voltage unbalance and protects the fault. Thus, transmission system can quickly return to operating in a conventional state. As a result we will expect improvement effect for the problems about voltage stability and protection scheme malfunction.

VI. SIMULATION RESULTS
Simulation results of this paper is as shown in Figs.5 to 9.

Fig.5. Simulation results using SFCL.

Fig.6. (a) and (b) Fault Current limiting, improvement in voltage unbalance within ¼ cycle.

A. Comparing The THD Values Of PID And Combined PID With SFCL
1. Signal-1:

Fig.7. THD value of signal-1 using PID and PID with SFCL.
TABLE I: Compression of THD Values with PID and Combined PID and SFCL

<table>
<thead>
<tr>
<th>Type of Control</th>
<th>Signal 1</th>
<th>Signal 2</th>
<th>Signal 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>PID</td>
<td>0.38%</td>
<td>0.36%</td>
<td>0.34%</td>
</tr>
<tr>
<td>PID &amp; SFCL</td>
<td>0.19%</td>
<td>0.12%</td>
<td>0.11%</td>
</tr>
</tbody>
</table>

VII. CONCLUSION

This work simulated in MATLAB Simulink and results are compared with the reference paper [PID Controller] [15]. This paper proposed a method to reduce voltage unbalance for a PID compensated transmission line using SFCL. First, the configuration and operation of a compensated transmission line connected electric railway system were modeled and detailed. Next, voltage unbalance in transmission line was studied when line fault occurs. Finally, the method for alleviating this problem with SFCL was considered. The proposed method showed the following improvements for transmission line faults: (1) The fault current was decreased and (2) Balancing voltage in the transmission line system was quickly improved after fault was removed in the transmission system. Electric railway system returns to steady state with fast operation within ¼ cycle.

VIII. REFERENCES


Fig.8. THD value of signal-2 using PID and PID with SFCL.

Fig.9. THD value of signal-3 using PID and PID with SFCL.
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[9] A Novel Collaboration Compensation Strategy of Railway Power Conditioner for a High-Speed Railway Traction Power Supply System Chenmeng Zhang(Student), Baichao Chen, Chao Cai, Mengkui Yue, Cuihua Tian, Bo Chen, Jiaxin Yuan


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