Optimizing the Location and Size of SVC to Compensate the Railway's Voltage Drop and a Novel Approach for Controlling SVC

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Abstract*:* With increasing focus on economical as well as environmentally friendly means for mass transportation, railways are gaining a special momentum in many countries. Traction loads are one of the most difficult types of loads feeding by an electrical utility and causes complications not only for the utility but also for Railway Company. One of the effective solutions for improving the power quality of the electric railway is to install static VAr compensators (SVCs) in the traction substations. This paper discusses a new technique for controlling SVCs in railway systems with the aim of compensating the voltage drop at the point of connection of the locomotives to the railway main line. Also the location and size of the SVC is optimized by Particle swarm optimization (PSO) algorithm. A complete model of the SVC with its control circuit is set up and simulated by PSCAD program. The simulation results show appropriate improvement in the voltage profile of locomotive in the point of connection to the railway main line. Also the results show the ability of proposed control system to eliminate the voltage oscillations.

Index Terms- Traction systems, Voltage drop, SVC, TCR/FC, PSO.

1. INTRODUCTION

In recent years, several kinds of traction system configurations have been used across the world. Choosing the system depends on the train service requirements, such as commuter rail, freight rail, light rail, train loads, and the electric utility power supply [1]. Railway is a suitable device for regular mass transportation. It is remarkably energy-saving in comparison with automobiles and aircraft. Therefore, railways have such big potentiality as to solve global environmental issues of carbon oxide emission if they replace the automobiles or aircrafts [2]. According to the recent studies, some of the main features of railways can be named as fast speed [3], safe transportation [4], less pollution [5], improving the voltage profile [6-7], high accessibility [8], etc.

The function of traction systems is to deliver power to the locomotives as efficiently and economically as possible [9-10]. Most of the main line electrified railway system operates at 25 kV 50/60 Hz. The power of Locomotives is obtained from a single phase overhead contact feeder via a feed transformer to the public utility system. At this voltage level, traction systems face many difficulties which are not only harmful to the traction system itself, but also may spread through the supply grid or disturb other users in the same grid. Many of these problems originate from the load mobility [10]. Electric locomotives running on the electrified railroads are of single-phase, large power and nonlinear loads [11]. These kinds of loads cause significant negative-phase-sequence and harmonic currents in the public power network which can affect the power quality of the system [12]. The adverse effects of harmonics in power systems include overheating of rotating machines, overloading of capacitors, interference with communication, signaling and electronic circuits, overstressing of insulation, errors in metering and possible system resonance [13]. In extreme cases, overvoltage can be produced and small machines and capacitors can be burned out [14]. In particular, harmonic distortion can lead to a higher voltage form factor and hence a lower locomotive power output [15]. Furthermore, traction loads cause flicker when the trains pass from one substation to another. Predicting the flicker is sometimes very difficult because its changing depends on the generation pattern, system dynamics, etc [1].

Another problem that generally affects the 25kV railway systems is the voltage drop at the connection point of the locomotives to the railway main line. This issue is fundamentally caused by passing the lagging reactive current in the inductive components of the overhead system [10], [16]. Regulating the voltage so that the trains operate normally, limit both the maximum length of the track section (typically 25 km) and the distance between feeding substations, as shown in Fig.1. Furthermore, these voltage drops influence the maximum power transmitted by the feeder, involving a limit in the maximum numbers of locomotives feeding simultaneously [10], [17] and [18].

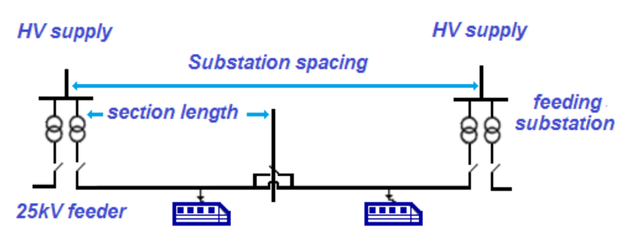


Fig.1. Typical feeding arrangement of an electrified railway system [10]

Generally, voltage drop not only will influence the power of the electric locomotive and reliability of power supply of traction transformer, but also it will pollute the quality of network severely when the operating security of local power network will be harmed if no compensation strategy is made [19].

Accordingly, this paper studies a 25 kV railway electrification system. At this voltage level, the railway system is usually divided into electrical sections of about 25 km length. Longer sections result in an excessive voltage drop with severe loss of performance to the most distant locomotives [16]. Feeding longer track section is normally possible by installing additional substations but it is an expensive process. Therefore, it is necessary to investigate proper methods for extending the viable length of track section more than 25 km. In railway systems, because of the frequently changed dynamic load, passive equipment cannot adjust the compensating capability to the load needs, where over- and under-compensation occur frequently [20]. By using Static Var Compensators (SVCs), the voltage drops can be decreased. The SVCs are controllable reactive power sources, involving controlled or variable capacitors or inductors. It is proved that a conventional Thyristor Controlled Reactor (TCR) in parallel with a fixed capacitor (FC) can sufficiently follow the traction load changes [10]. Earlier studies have proved that by using two SVCs which are respectively connected to the middle and end of the feeder, section lengths can be increased up to 75 km [21-22]. Also It has been proposed by Morrison et al [23] that SVCs can be applied to electric railway systems to provide voltage support and consequently permit the doubling or possibly the tripling of the normal feeder length.

As regards the optimization tool, this paper makes use of the Particle Swarm Optimization (PSO) method to find the optimal location and size of the SVC on the electrified railways. Then with a modified control of SVC, one TCR/FC is used instead of two of them to compensate the voltage drop over the main line of railway's supply with length equal to 75 km. In the previous studies, the SVC control signal was its own voltage. However, this method can only regulate the voltage at the SVC connection point and it is unable to regulate the voltage in other points over the railway line. Here the voltages in 4 different points (locomotives connection points to the line) are recorded and sent to the SVC control system. The control system is designed in a way to compensate voltage of the point which has the minimum value among the 4 points. Through this strategy, the number of SVCs can be reduced from 2 to 1 in railway lines with length of 75 km. The other modification made in the control system is using a dead-band which reduces the chattering in the thyristors firing angle. The rest of this work is organized as follows: Section 2 introduces some basic concepts of PSO. Optimizing the location and size of SVC with the use of PSO are discussed in section 3. Section 4 represents the system's model and characteristics which are used for simulations. Then in section 5, we propose a novel approach to control the SVC so that to regulate the minimum voltage along the railway line and also eliminate the voltage oscillations by controlling a feedback voltage. Finally, the results of the simulations are represented in section 6 and are compared with case of not using SVC and also case of using SVC but with the conventional control system. Finally, the main concepts and contributions of the work are summarized in Section 7.

2. THE THEORY OF PARTICLE SWARM OPTIMIZATION (PSO)

In recent years, a number of computational techniques inspired by biological systems are proposed. Examples are artificial neural network (ANN) [24] inspired from the human brain, genetic algorithm (GA) which is inspired from the human evolution and Particle swarm optimization (PSO) that is inspired from the social behavior of bird flocking or fish schooling. The PSO algorithm is a population based stochastic optimization technique in which the potential solutions (called particles) fly through the search-space by following the current optimum particles. This process is according to the simple mathematical formulae based on the particle's position and velocity [25]. In every iteration, the position of each particle is updated by following two "best" values. The first one is the best experience of each solution called ***pbest***. The other "best" value is the global best particle called ***gbest***. After finding these two best values, the particle updates its velocity and positions as follows [25]:

$$V_j^{k+1} = W \times V_j^k + C_1 \times r \times (pbest_j - X_j^k) + C_2 \times r \times (gbest - X_j^k) \quad (1)$$

$$X_j^{k+1} = X_j^k + V_j^{k+1} \quad , j = 1, 2, ..., N_{sw} \quad (2)$$

where V_j^k is the velocity of j^{th} particle in k^{th} iteration, X_j^k is the position of j^{th} particle in k^{th} iteration, r is a random value in the range [0,1], C_1, C_2 are learning factors which usually equal to 2 and N_{sw} is the number of swarms in the population.

One significant feature of PSO is that it's not necessary that the optimization problem be differentiable because PSO doesn't use the gradient of the problem [26]. Some of the advantages of PSO in comparison with GA are that PSO is easy implementation and fewer setting parameters. Generally, PSO can be applied to any irregular and time variable optimization problem.

3. OPTIMIZING THE LOCATION AND CAPACITY OF TCR BY USING PSO

As mentioned previously, the main purpose of this paper is to compensate the voltage drop of the railway main feeder using a TCR/FC device. In this section, PSO is used to optimize the location and size of SVC. For this purpose, MATLAB programming is used to determine the best location and also the most optimal size of SVC so that the voltages of the locomotives' connection points to the railway main line don't be less than 25.2 kV. In this analysis, the movement of locomotives has been taken into account by supposing that the track sections are divided into four equal sections and the distance between two locomotives is constant (equal to 18.75 km). The distance of the first locomotive from feeding substation is varying in the range 0-18.75 km. With running this program, in each step, the distance of the first locomotive from feeding substation is increased as 1 km and therefore at the end of running the program we have eighteen different locations. Thus, for each run of the program, we will obtain 72 different locations for the locomotives. In fact, the output of the program is eighteen different voltages where each of these voltages is the minimum voltage between those of four locomotives at each step. The least voltage of these eighteen locomotives has been chosen and then by using PSO, the size of SVC has been computed so that this minimum voltage doesn't be less than 25.2 kV. The steps of this algorithm are described at below:

step1: Input data such as C_1‚C_2 and initial particle's position (initial location and capacity of SVC), etc;
step2: Pick random location and capacity for each particle;
step3: Run the load flow program and compute all the level of voltages for all locations;
step4: Choose the best location as ***gbest*** and the best experience of particles ***pbest*;**
step5: Check all parameters to be in the limited ranges;
step6: Run the load flow program and compute all the level of voltages for all locations;
step7: Update ***gbest*** and ***pbest*;**
step8: Check th**e** termination criteria of the algorithm; If the termination criterion is met, print the results otherwise back to step7.
Here, the control variables are the location of locomotives which is randomly varying between 0-75 km and the size of SVC that can take any continuous value in the range of 0-20 MVAr. The termination criterion for the optimization process is to reach the minimum voltage of locomotives at the point of connection to the railway main line such that it doesn't be less than 25.2 kV. The active and reactive powers for each train are assumed to be respectively equal to 2.25 MW and 1 MVAr, respectively. Table 1 shows the result of 10 times running of PSO algorithm to obtain the optimum size and location of the SVC. Due to the statistical nature of PSO method, we've got a different value in each running. In Table 1, the parameter d_{SVC} is the SVC distance from the main station (km), Q_{SVC} is TCR capacity (MVAr) and v is the locomotive voltage at the connection point to the railway main line (kV).

Table1. Optimization results; $\boldsymbol{d_{SVC}}$ (km), $\boldsymbol{Q_{SVC}}$ (MVAr) and v (kV)

$\boldsymbol{d_{SVC}}$	**63**	**57**	**59**	**58**	**58**	**57**	**63**	**58**	**61**	**58**
$\boldsymbol{Q_{SVC}}$	**4.077**	**4.444**	**4.336**	**4.401**	**4.442**	**4.4922**	**4.490**	**4.441**	**4.184**	**4.435**
$\boldsymbol{v}$	**25.21**	**25.22**	**25.25**	**25.25**	**25.29**	**25.27**	**25.20**	**25.29**	**25.24**	**25.28**

According to Table 1, the optimal operating point is $\boldsymbol{d_{SVC}}$= 57 km, $\boldsymbol{Q_{SVC}}$= 4.4435 MVAr. Fig. 2 shows the growth procedure to obtain this location and size for SVC. In the next section, we have introduced a reliable model for railway system and have installed a TCR/FC at this optimal operating point to compensate the voltage drop of locomotives.

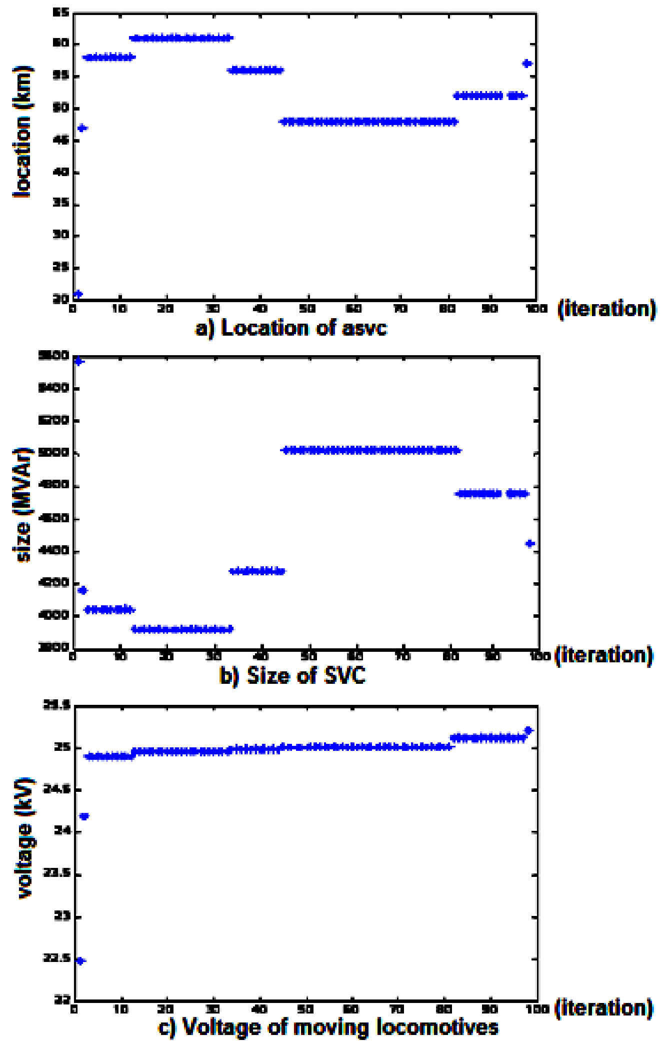


Fig.2. Process of obtaining size and location of SVC for optimized point which is chosen from Table 1 ($\boldsymbol{d_{SVC}}$= 57 km, $\boldsymbol{Q_{SVC}}$= 4.4435MVAr); a) Finding the location of SVC in term of km; b) Finding the size of SVC in term of MVAr; c) Regulating the voltage of locomotives in the connection point to railway main line.

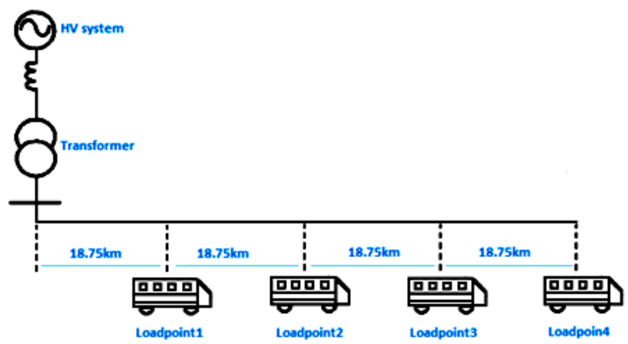


Fig.3. Schematic of 25kv electrification system [16]

4. SYSTEM DESCRIPTIONS

4.1. Single track section

To study the voltage drop at the point of locomotives connection to the railway main feeder, modeling a traction system including several locomotives and the compensator (TCR/FC) is necessary. In this paper, studies are carried out on the 25 kV electrification systems for main line railways (Fig.3).The single track section is fed trough a single phase step down transformer from the high voltage supply which is modeled by an inductor.

As it can be seen from Fig. 3, the whole length of 75 km feeder is equally divided into four parts of 18.75 km such that at the end of each part would be a connection point as a loading point. Each of these parts is modeled by a π-equivalent circuit (Fig.4) with a longitudinal impedance of (3.17+j0.0258) Ω/km at 50 Hz and a shunt capacitance of 0.375µF/km.

As shown in Fig.4, the movement of locomotive along the railway line has been modeled by considering the time variable line impedance for the first section. Here, ***d*** is the distance of the first locomotive from the feeder section that changes in the range 0-18.75 km. The other locomotives have a constant distance from each other equal to 18.75km. Various locomotive positions distributed along the feeder system can be selected for study.

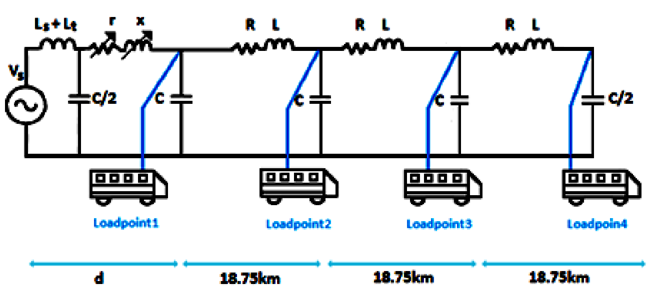


Fig.4. Equivalent circuit of a 75 km track section

4.2. Locomotive Models

Depending on the aim of studies (voltage drops or harmonics), two different models are used for locomotive:

- A constant current, constant power factor model, including a single diode bridge which is suitable for voltage regulation simulations;
- A full representation for harmonic and dynamic studies. This model is including conventional thyristor converters which are used with delayed firing to control the current in lower speed ranges. However, most of the time these converters operate without any firing delay and speed increasing is achieved by field weakening [6].

Fig. 5 shows a simplified model of locomotive that is used in this paper. In this model, it is assumed that the transformer voltage ratio is 1:1. The parameters of the railway system using in this paper are shown in Table 2.

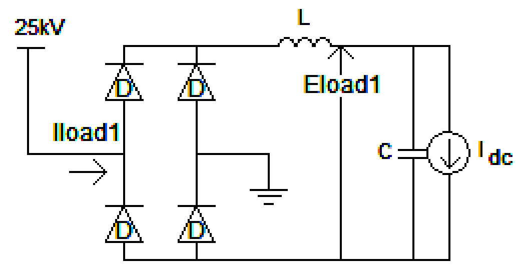


Fig.5. Simplified model of locomotive for voltage drop studies

Table 2. System parameters

Element	**Value**
Vs	*25.2kV*
Rs + Rt	*1 Ω*
Ls + Lt	*0.0271H*
R (Line Sec.)	*3.17 Ω*
L (Line Sec.)	*0.0285H*
C (Line Sec.)	*0.0375µF*
L (each Loco.)	*0.05H*
I (each Loco.)	*0.068A*

5. PROPOSED CONTROL SYSTEM

In the previous studies, SVC is assumed to only control and regulate the voltage across itself. The new idea used in this paper is to regulate a feedback voltage by SVC. This feedback voltage is defined as the minimum of locomotives' RMS voltages along the railway line, called V_C. As shown in Fig.6, firstly the RMS voltages of four locomotives should be computed. Then, the minimum voltage between these four voltages is considered as V_C.

By using this minimum voltage, we made the signal ***aa*** so to determine the firing angle of the TCR's thyristors to compensate the voltage drop at the point of connection the locomotives to the railway's main line. The other new idea which is used in the proposed control scheme is creating a dead band (25kv< V_C<25.4kv) to eliminated the oscillations of locomotives' firing angle. This is done by using two comparators as the second input of the integrator. The output of these two comparators is shown in Table 3. Fig. 7 shows the comparative thyristor firing angel in the two cases of 1) using the proposed method to eliminate the oscillations and 2) using the traditional methods in the area. This figure clearly shows the effectiveness of the proposed method.

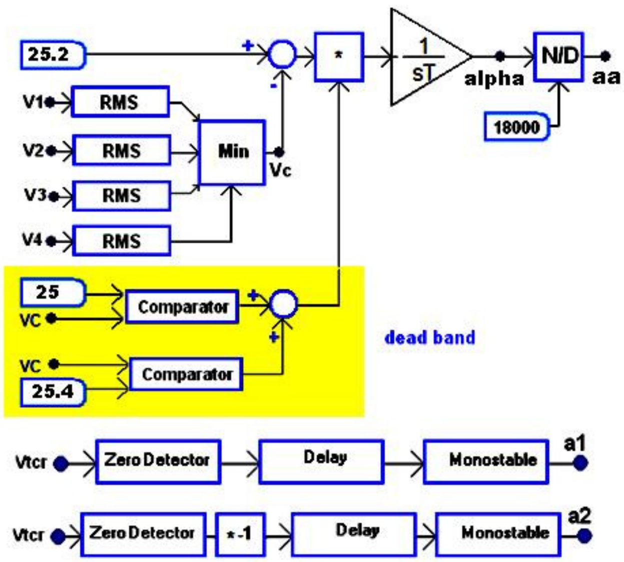
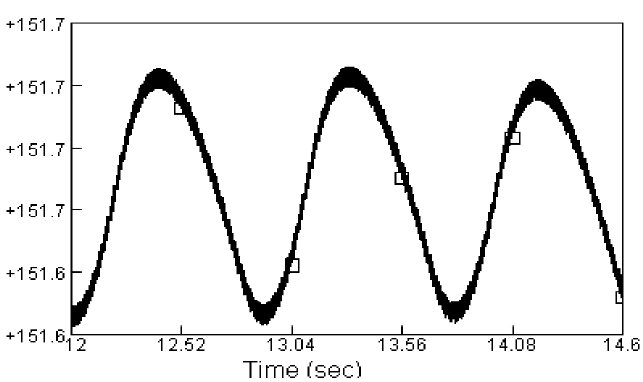


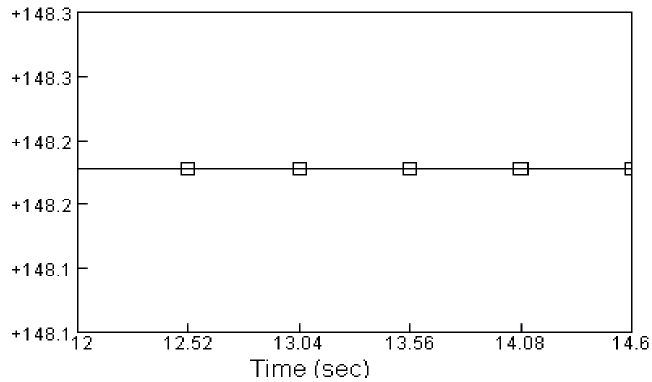
Fig.6. Proposed control system for SVC

Table3. Performance of dead band

Changes of Vc	Output of two comparators
25 kV < Vc < 25.4 Kv	0
Vc < 25 kV	1
Vc > 25.4 kV	1



(a)



(b)

Fig 7. Thyristor firing angle using a) Conventional method b) Proposed method

6. SIMULATIONS AND RESULTS

After optimizing the location and size of SVC by using PSO, the operating point of ($\boldsymbol{d_{SVC}}$=57km, $\boldsymbol{Q_{SVC}}$= 4.4435 MVAr) is selected as the optimizing point. In this section, SVC has been installed at this point to compensate the voltage drop. The arrangement of the TCR/FC that is used in this paper is shown in Fig.8. Also, Table 4 shows the characteristics of this compensator.

Table 4. Chaharctristics of SVC

Element	Value
Lf	*0.055H*
C (TCR + Filter)	*22µF*
LTCR	*0.4H*

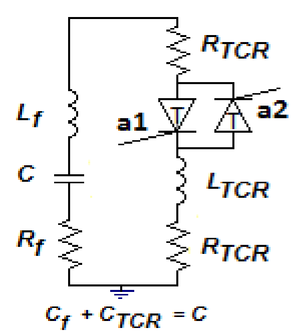


Fig.8. Arrangement of SVC using in compensation

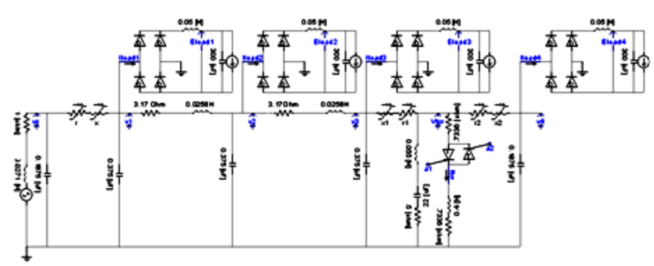


Fig.9. PSCAD diagram of the compensated system

Table 5. Different case using for voltage drop studies

Case / *variables*	**1**	**2**	**3**	**4**
d (km)	**18.75**	**10**	**1**	**1**
i (A)	**68**	**68**	**68**	**6.8**

Table 6. RMS voltages of 4 locomotive connection points to the line in term of kV in different cases of Table 5

Case	Compensation Method	V1	V2	V3	V4
1	No SVC	21.2	20.9	20.3	20
	SVC with conventional control method	24.2	24.3	25.2	24.8
	SVC with proposed control method	25	25.2	26.8	26.3
2	No SVC	22.8	21.7	21.1	20.8
	SVC with conventional control method	24.3	24.2	24.7	24.9
	SVC with proposed control method	25.1	25.5	26.5	26.8
3	No SVC	23.7	22.5	21.8	21.5
	SVC with conventional control method	24.7	24.3	24.5	25.3
	SVC with proposed control method	25.2	25.3	26.1	26.9
4	No SVC	25.2	25.2	25.2	25.2
	SVC with conventional control method	25.3	25.3	25.3	25.3
	SVC with proposed control method	25.2	25.3	25.4	25.5

Fig.9 shows a more detailed PSCAD diagram of this compensated railway system. The simulations are run for 4 different cases and the results are shown in Table 5. The variables for each case are ***i*** (DC current of the locomotives) and ***d*** (distance of the first locomotive from the substation).

Table 6 shows the RMS voltage value at locomotive connection points to the main railway electrical line for the different cases with different control schemes. Here, case 1 is the worst case in which four locomotives are simultaneously fed from the substation and the fourth locomotive is at the furthest point of substation (which is 75km). From Table 6, for case 1 with no SVC, the maximum voltage drop is 20% (V4= 20 kV) while with using the proposed control method in all cases all voltages are in the acceptable range. However, the conventional SVC control scheme that regulates the voltage at the SVC point is unable to compensate the voltage drop in all cases (here there are some connection points with voltages below than 25 kV). On the other hand, for case 4 that simulates the no-load case of the system, the performance of both conventional and proposed methods are acceptable.

7. CONCLUSION

In this paper, the location and size of SVC over the main line of the railway was optimized using PSO. Also, a novel approach for controlling the SVC was proposed. The proposed method unlike the conventional method is able to regulate the voltage in all locomotive connection points to the railway line. It was shown that with the proposed method, only one SVC is enough for a railway with length equal to 75 km. The simulation results showed the satisfying performance of the proposed method for compensating the voltage drop in the railway feeders.

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