Model for Optimal Balancing Single-Phase Traction Load Based on Steinmetz's Method

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***Abstract* -- Steinmetz's method based on correction of the unbalanced load to a fully balanced one with unity power factor is widely used for balancing large scale single-phase traction load. This paper presents a model for balancing shunt compensators which extends the shunt compensators' capacity to providing any desirable levels of the system balancing and reactive power compensation. The model includes systems constraints and provides an optimal solution. Based on this model, the analysis of the shunt compensators' parameters is performed for full and partial balancing with the focus on reducing compensation capacity of reactive power equipment. According to the mathematical analytic solution of the optimal model, the calculation results are given with MATLAB for different load and object conditions, which demonstrate the advantages of the optimal method proposed.**

***Index Terms*--single-phase traction load; balancing; system model; compensation capacity.**

I. INTRODUCTION

With the growing of traction loads of electric railway in the public electric power systems, the power quality problem caused by traction loads in surrounding grids needs to be addressed in a new and serious way. The connection of a large scale AC single-phase traction load to the three-phase network results in a certain voltage unbalance. That affects other consumers in the same grid. The negative sequence current will be inevitably caused by the unsymmetrical feeding system of electric railways, which may result in an unacceptable negative-phase sequence voltage in the power system if no countermeasures were taken. The fixed or automatically adjusted reactive power compensation apparatus, such as Static Var Compensator (SVC) and Static Var Generator (SVG), are normally installed in traction substation to improve the power factor, to alleviate the voltage fluctuation and to reduce the negative phase sequence current [1-6].

At present the most commonly used technique for balancing single-phase traction load in electric railway is based on the well known Steinmetz's method used for calculation of the SVC's parameters [5-9]. The balancing SVCs based on Steinmetz's method provide full compensation for both the negative sequence current and the reactive component of the positive sequence current produced by the single phase traction load and so convert the traction load into an equivalent balanced load with unity power factor. This method is very suitable for many single phase traction loads with the simple correcting elements and high level reactive power compensation. However, the balancing SVCs require installation of primary ratings which consequently incur considerable capital costs.

This paper figures out a way to minimize the required compensation capacity based on Steinmetz's circuit under the appropriate constraints of voltage unbalance and power factor[10-13]. Firstly, a model based on Steinmetz's circuit was built to find a minimal total required capacity, which can not only compensate the reactive power, but also decrease the negative sequence current to a level acceptable for practical applications. The full and partial balancing techniques are studied on the basis of the developed generalized model based on Steinmetz's circuit. Then the mathematical solution was deduced using the optimal theory. Finally, the results are illustrated by a typical system example.

II. SYSTEM MODEL

The famous Steinmetz's circuit, as shown in Fig.1, is used for balancing a single-phase traction load in a three-phase system. The single-phase traction load is connected between A phase and C phase, and is labelled by $S_L = P_L + jQ_L$, where P_L is the active power, and Q_L the reactive power. Based on the general theory of load balancing, it is then necessary to have a capacitor connected between A and B phase and a resistor connected between B and C phase in order to balance a purely active load. For an inductive traction load, it needs to add a capacitor between C and A phase to correct the power factor.

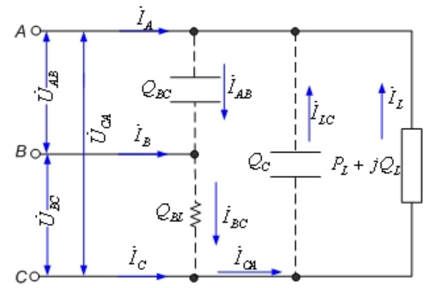

Fig.1 Steinmetz compensation circuit

When a single-phase traction load is connected to a power network, one essential condition is that the voltage unbalance caused by this load on the three-phase power network must not leads to a harmful effect on other loads. Induction motors are particularly sensitive since they are subjected to supplementary losses when their supply voltages are unbalanced. As is well known, voltage unbalance is expressed by the symmetrical components as the ratio of the negative-sequence component to the positive sequence component. Reduction of negative sequence voltage and reactive power compensation are common targets for balancing systems with SVC based on Steinmetz's circuit.

In an IEC publication it is mentioned that motors shall be capable of withstanding an unbalance of

$$\varepsilon_U = \frac{|\dot{U}_-|}{|\dot{U}_+|} \times 100\% = 2\% \qquad (1)$$

The subscript – and + denote the negative and positive sequence component respectively. Therefore, the first additional constraint equation can be formulated as:

$$0 \le \varepsilon_U \le 0.02 \qquad (2)$$

Similarly, current unbalance is expressed as

$$\varepsilon_I = \frac{|\dot{I}_-|}{|\dot{I}_+|} \times 100\% \qquad (3)$$

If we consider that S_L is the apparent power of a traction load and S_d is the fault level (short-circuit power) at the feeding point of the power supply system, we can get the equation [10]:

$$0 \le \varepsilon_U = \varepsilon_I \frac{S_L}{S_d} \le 0.02 \qquad (4)$$

If φ is the power factor angle of the whole system furnished with SVC devices, the reactive power compensation requirement can be formulated as PF (power factor) cosφ:

$$0 \le \cos\varphi \le 1 \qquad (5)$$

The power factor limit is usually specified in the range of 0.9-1. To the above, constraint can be added the one that the system voltage will be within a tolerable range at the PCC. The expression for this constraint is formulated as follows:

$$0.9 \le \cos\varphi \le 1 \qquad (6)$$

The system of non-linear algebraic equations combined together with the constraint expressions (4)—(6) gives full range of possible solutions for parameters of the SVCs based on Steinmetz's circuit which provides the targeted system conditions.

In Fig.1, the total power rating (a sum of absolute values of the compensation capacity of the phase-to-phase) required for balancing a traction load with SVC based on Steinmetz's circuit can be expressed as

$$f(Q_{BL}, Q_{BC}, Q_C) = Q_{BL} - Q_{BC} - Q_C \qquad (7)$$

Where Q_{BC} is the size of the capacitor between A and B phase, Q_{BL} is the size of the reactor between B and C phase. Q_C is the size of the capacitor between C and A phase. Q_{BC} and Q_C take negative values for a capacitive power. To avoid the over compensation of the reactive power, the resultant reactive power for the total system should be greater than zero. This constraint can be formulated as:

$$Q_{BC} + Q_{BL} + Q_C + Q_L \ge 0 \qquad (8)$$

So considering the constraint expressions (4) — (8), mathematical equations for minimizing the total power rating required to balance an inductive traction load based on the Steinmetz's circuit can be formulated as:

$$\begin{cases} Min \quad f(Q_{BL}, Q_{BC}, Q_C) = Q_{BL} - Q_{BC} - Q_C \\ s.t. \\ \qquad Q_{BC} + Q_{BL} + Q_C + Q_L \ge 0 \\ \qquad 0 \le \varepsilon_U = \varepsilon_I \dfrac{S_L}{S_d} \le 0.02 \\ \qquad 0.9 \le \cos\varphi \le 1 \end{cases} \qquad (9)$$

MATHEMATICAL ANALYTIC SOLUTION FOR THE SYSTEM MODEL

The mathematical analytic solution of the optimal model for balancing a traction load can be derived. The relationship between the phase to phase currents and line currents in Fig.1 can be expressed as

$$\begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} \dot{I}_{AB} \\ \dot{I}_{BC} \\ \dot{I}_{CA} \end{bmatrix} = \begin{bmatrix} \dot{I}_A \\ \dot{I}_B \\ \dot{I}_C \end{bmatrix} \qquad (10)$$

Let the optimal compensation capacity Q_{BC}、Q_{BL}、Q_C have the relation

$$\begin{cases} Q_{BC} = -h_1 P_L \\ Q_{BL} = h_2 P_L \\ Q_C = P_L (h_3 - \tan\varphi_L) \\ h_i \ge 0, \quad i = 1, 2, 3 \end{cases} \qquad (11)$$

φ_L is the power factor angle of the traction load.

By the Symmetrical component method, the current unbalance and power factor can be derived as:

$$\begin{cases} \varepsilon_I = \dfrac{1}{2}\sqrt{\dfrac{(h_2 - h_1 - 2h_3)^2 + \left[\sqrt{3}(h_2 + h_1) - 2\right]^2}{1 + (h_2 - h_1 + h_3)^2}} \\ \cos\varphi = \dfrac{1}{\sqrt{1 + (h_2 - h_1 + h_3)^2}} \end{cases} \qquad (12)$$

So the optimal model becomes a non-linear programming problem. According to the Kuhn-Tucker' conditions, optimal solution for this non-linear programming problem can be obtained as:

$$\begin{cases} Q_{BC} = (\dfrac{\sqrt{1-C^2}+\mu}{3C} - \dfrac{1}{\sqrt{3}})P_L \\ Q_{BL} = (\dfrac{1}{\sqrt{3}} + \dfrac{\sqrt{1-C^2}-2\mu}{3C})P_L \\ Q_C = (\dfrac{\sqrt{1-C^2}+\mu}{3C} - \tan\varphi_L)P_L \\ Q_{\min} = (\dfrac{2}{\sqrt{3}} + \tan\varphi_L - \dfrac{\sqrt{1-C^2}+4\mu}{3C})P_L \\ 0 \le \dfrac{\sqrt{2}}{2}\mu\dfrac{S_L}{S_d} = \varepsilon_U \le 0.02 \\ 0.9 \le C \le 1 \end{cases} \tag{13}$$

Where P_L is the active power of the traction load, φ_L is the power factor angle of the traction load, S_L is the apparent power of a traction load, S_d is the fault level (short-circuit power) at the feeding point of the power supply system, μ is the constant and C is the compensated systems' power factor.

The above representation of the compensation components by (13) extends the capability of balancing single phase traction load to providing any power factor for the SVCs based on Steinmetz's circuit.

III. FULL BALANCING OF SINGLE-PHASE TRACTION LOAD

The requirement of full balancing simplifies (14) to the equation $\varepsilon_\mu = 0$ and unity power factor (C=1). The "Steinmetz formula" relates the installed phase to phase compensation components to the active power of the load as follows:

$$\begin{cases} Q_{BC} = -\dfrac{1}{\sqrt{3}}P_L \\ Q_{BL} = \dfrac{1}{\sqrt{3}}P_L \\ Q_C = -\tan\varphi_L P_L \end{cases} \tag{14}$$

According to (14), the total capacity used with full balancing by the Steinmetz's circuit is then given by

$$S_{\text{total}} = |Q_{BC}| + |Q_{BL}| + |Q_C| = \left(2/\sqrt{3} + \tan\varphi_L\right)P_L \tag{15}$$

The chart shown in Fig.2 illustrates the compensation capacity calculated from (14) for the condition of the traction load PF varies in the range of 0.7 -1 (lag.). It can be seen that the absolute values of the compensation rating Q_{BC} (between A and B phase) and Q_{BL} (between B and C phase) are fixed and unchanging. The total power rating of the balancing SVCs proving full balancing in the system varies with the power factor of single-phase traction load. The total required power ratings at the lower power factor are higher than at the higher power factor.

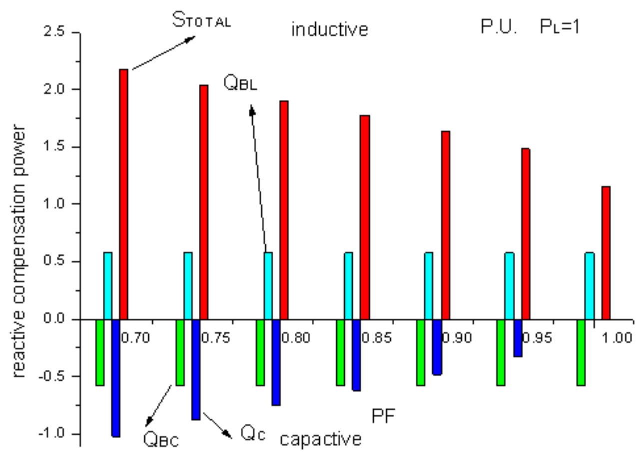

Fig.2 SVCs phase to phase compensation capacity calculated for full balancing single phase traction load

IV. PARTIAL BALANCING OF SINGLE-PHASE TRACTION LOAD

Partial balancing of SVCs can be applied in the systems where complete elimination the negative sequence is not required. In fact, majority of power systems can tolerate negative sequence voltage levels from 1% to 2% of the positive sequence voltage. In the terms of balancing this allows SVCs be designed for only partial reduction of negative sequence current by the single-phase traction load. Elaborating of this point is important reserve for reduction of SVCs power ratings. Taking into account the subject of limitation, the equation (13) is an analytic solution for the optimal model of partial balancing single-phase traction load.

For practical applications, appropriate values for PF and ε_μ can be selected, this will decrease effectively the installed compensation capacities. The reduction of compensation capacity based on the above optimal solution of partial balancing model compared to full balancing model's formulas can be obtained as

$$\Delta S_{\text{total}} = \frac{\sqrt{1-C^2}+4\mu}{3C}P_L \tag{16}$$

According to (15) and (16), we can get

$$K_Q = \frac{\Delta Q}{S} = \frac{\sqrt{1-C^2}+4\mu}{3C\left(2/\sqrt{3}+\tan\varphi_L\right)} \times 100\% \tag{17}$$

For high speed railways, the EMUs (electric multiple unit) are of AC-DC-AC drive type, which are controlled by the PWM technique. The power factor of the EMU is near to 1 and no reactive power needs to be compensated. In this situation, (17) becomes

$$K_Q = \frac{\Delta Q}{S} = \frac{\sqrt{1-C^2}+4\mu}{2\sqrt{3}C} \times 100\% \tag{18}$$

V. ANALYSIS OF POWER RATINGS FOR OPTIMAL BALANCING MODEL

Supposing the traction load active power P_L=1.0p.u. Assuming S_d=200MVA and $S_L \leqslant$10MVA, power systems can tolerate negative sequence voltage levels from 0 to 2%, according to eq. $\varepsilon_\mu = \varepsilon_I \frac{S_L}{S_d}$, we can define the range of negative sequence current levels ε_I from 0 to 0.02τ. Therefore, τ increases with the range of negative sequence current levels $\varepsilon_I$increasing. On the other hand, τ decreases with the range of negative sequence current levels ε_I decreasing. Accordingly the value of ε_I is the range of 0 to 0.39 and the value of μ is the range of 0 to 0.551.

The charts Fig.3 show the phase-to-phase compensation capacity and total power ratings calculation with μ in the range of 0 to 0.551 and P_L=1.0p.u with $\cos\varphi_L = 0.9$.

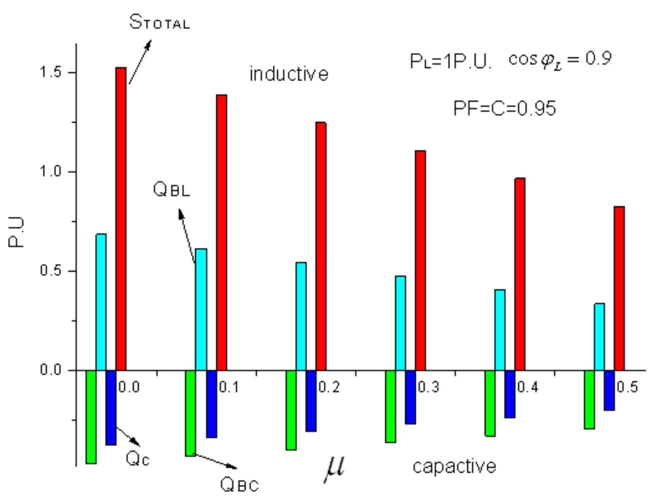

Fig.3 SVCs phase to phase compensation capacity calculated to provide PF=0.95 and $\varepsilon_\mu \le 0.02$ for balancing single phase traction load

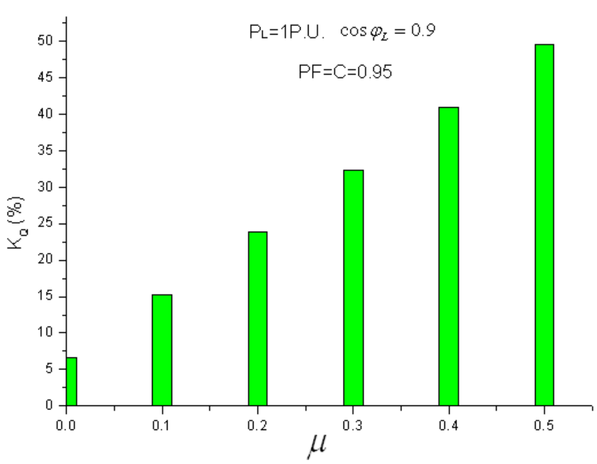

Fig.4 The curve of ΔQ versus μ at PF=0.95

The charts in Fig.3 and Fig.4 show when the limiting value of power factor C is constant, the limiting value of current unbalance μ increases with the increase of reduction capacity ΔQ. So, an optimal compensation capacity can be obtained by regulating the limiting value of the current unbalance and the power factor respectively. When μ varies from 0 to 0.551, the reduction capacity used by optimal method is approximately 0~50% of that used full balancing based on Steinmetz method.

Let the target conditions V_2=1% of the nominal voltage, if the electric locomotive is AC-DC drive electric locomotive with the rating of 4.8MW and the power factor of the traction load is 0.86 (μ=0.5).The PF varied from 0.9 to 1. The principle about phase-to-phase compensation capacity varied with the limit value of power factor is got from the Fig.5 and Fig.6.

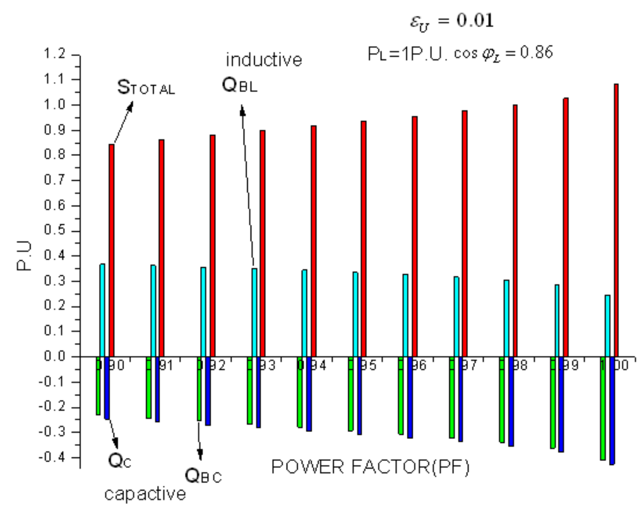

Fig.5 SVCs phase to phase compensation capacity calculated to provide $\varepsilon_\mu = 0.01$ and PF varied from 0.9 to 1 for balancing single phase traction load

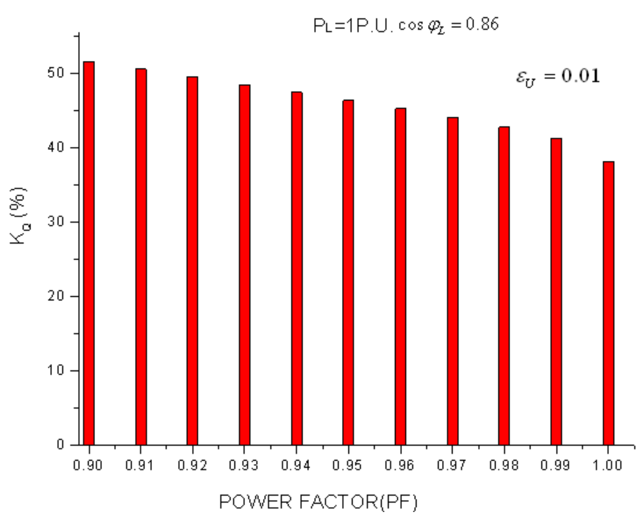

Fig.6 The curve of ΔQ versus PF at $\varepsilon_\mu = 0.01$

The charts in Fig.5 and Fig.6 show the rules, when the limiting value of current unbalance μ is constant, the limiting value of power factor C increases with the decrease of reduction capacity ΔQ.

As shown by Fig.2 to Fig.6, the simulation results as follows. Steinmetz's method and the full balancing with target PF=0 and negative sequence voltage limit value is zero, although meeting the system requirements, need the phase-to-phase compensation components to be of substantial size. The modified partial balancing method is the most economical for balancing single-phase traction load. When Sd=200MVA and SL⩽10MVA, the reduction capacity used by optimal method is approximately 0~50% of that used full balancing method based on traditional Steinmetz method. As the ratio of the short-circuit power and the traction load capacity is gradually getting bigger and the power factor of compensated system is gradually getting smaller, the reduction capacity used by optimal method of that used full balancing method based on traditional Steinmetz method is progressively greater. On the other hand, as the ratio of the short-circuit power and the traction load capacity decreases and the power factor of compensated system increases, the reduction capacity used by optimal method of that used full balancing method based on traditional Steinmetz method is progressive smaller.

As the optimal partial balancing method has the advantage of spending less compensation capacity, we can adopt optimal method to balance traction load for AC electric railway.

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