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Static Series Compensator for the compensation of voltage-quality disturbances based on particle swarm optimization techniques

Shazly A. Mohamed[1], A.A. Zaki Diab[2], N. Luo[3], T. Pujol[3], L. Pacheco[3]

[1] Department of Electrical Engineering, Faculty of Engineering, South Valley University, Qena, Egypt.
[2] Department of Electrical Engineering, Minia University, Minia, Egypt.
[3] Polytechnic School, University of Girona, Campus Montilivi, 17071 Girona, Spain.
Corresponding author: N. Luo, phone number: +0034 656475276, e-mail: ningsu.luo@udg.edu

Abstract – Static Series Compensator (SSC) is a power electronic based device that provides three-phase controllable voltage source to restore the load voltage to pre-sag conditions within few milliseconds. This paper proposes a new control technique based on an adaptive tunning PI controller that uses a selective controller to describe the effectiveness of SSC for mitigating voltage sags in power distribution systems at critical loads. The integral of time multiply squared error (ITSE) index is minimized to reach the optimal tuning of PI controllers based on particle swarm optimization (PSO) technique to determine whether the best fitting solution is achieved. The controller is designed in a synchronously-rotating reference frame. Independent (homopolar component, d-axis component and q-axis component) controllers are used to tackle balanced and unbalanced voltage supplies. Simulation is done using Simulink "SimPowerSystem" Toolbox to illustrate the principle and performance of an SSC operation in load voltage compensation.

Keywords
Static series compensator, voltage sags, particle swarm optimization, voltage source converter, control system.

1. Introduction

Power quality is a very important issue due to its impact on electricity suppliers, equipment manufactures and customers [1-2]. An important percentage of all power quality problems is of the voltage-quality type. Voltage sag is a momentary decrease in the RMS voltage magnitude in the range of 0.1 to 0.9 pu, with a duration ranging from half cycle up to 1 min. It is considered as the most serious problem of power quality, caused by the balanced or unbalanced faults in the distribution system or by the starting of large induction motors [3]. Among many different ways to mitigate voltage sags in power systems, the distribution static compensator and the SSC are the most effective devices; both of them based on the voltage source converter (VSC) principle [4]. SSC is a series-connected solid-state device that injects voltage into the system in order to regulate the load side voltage. It is normally installed in a distribution system between the supply and a critical load feeder at the so-called Point of Common Coupling (PCC) which is defined as the point of the network changes [5-6]. The primary function of SCC is to rapidly boost up the load-side voltage in the event of voltage sag in order to avoid any power disruption to that load. In addition to voltage sags and swells compensation, SSC can also have other features such as harmonic compensation, power factor correction and reduction of transients in voltage and fault current limitations [7-8].

There are various circuit topologies and control schemes that can be used to implement SSC [9-10]. PID control, Genetic Algorithm, fuzzy based approach are used to accommodate the response speed and overshoot [11-15]. In [16-17] design methods using the PSO algorithm are presented for determining the optimal PID controller parameters. In [18] a self-tuning PI controller is proposed to adjust controller gains using the PSO technique for a static synchronous compensator, in which an efficient formula for the estimation of system load impedance using real-time measurements is derived.

In this paper, a traditional two-level, three-phase pulse width modulation (PWM) inverter is used. In order to improve the effectiveness of SSC for mitigating voltage sags in power distribution systems at critical loads, PSO techniques are used for achieving the optimal tuning of the PI controller parameters. The proposed ontrol system is tested in different fault situations such as single, double, three-phase faults in order to validate the PSO based controller. The simulation results will show the performance of the proposed control algorithm.

2. SSC System

The SSC can compensate voltage sags by means of the injection of the inverter voltage through the series connected transformer [19]. Figure 1 depicts a SSC system with a series insertion transformer connected between the distribution transformer and the sensitive load. The electrical system viewed from the PCC is modeled as a three-phase voltage source with a shortcircuit impedance. Essentially, the SSC consists of a series-connected injection transformer, a voltage source inverter (VSI), a filter capacitor and an energy-storage device connected to the inverter DC link.

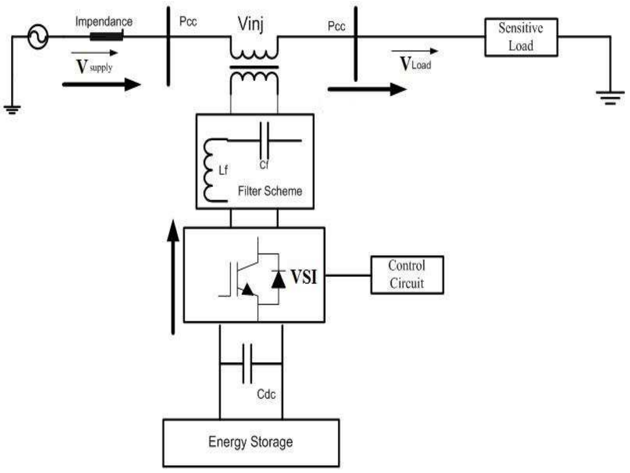


Fig. 1. Schematic diagram of a SSC system

The single-phase circuit shows that the SSC is nothing but a series voltage compensator [11]. Figure 2 shows the single-phase equivalent circuit used for studying the transfer function between the SSC inverter voltage V_{SSC} and the sensitive-load voltage V_L, where $L_{T'}$ and $R_{T'}$ represent the leakage inductance of the transformer and its equivalent series resistance, respectively. C_f is added to make a second-order filter together with $L_{T'}$ in order to filter the inverter output voltage. The voltage supply has been represented by a voltage source V_S with a short-circuit impedance R_{sh} and L_{sh} in series with a distribution transformer represented by its leakage inductance L_T and an equivalent resistance R_T. The sensitive load has been modeled by a parallel-connected R-L, the magnetizing branch of the transformer has been neglected. Finally, an additional load Z_P has been added after the distribution transformer.

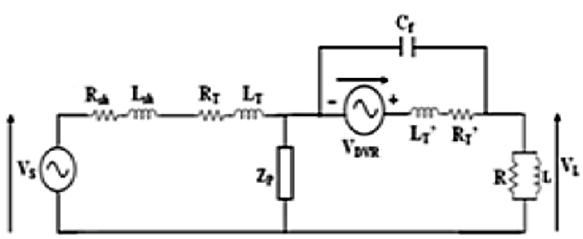


Fig. 2. Single-phase equivalent circuit of a SSC system

Figure 3 shows the frequency response for the SSC without the additional load Z_P (only sensitive load) and a very strong power supply is used (short circuit power = 20 pu), this result also holds when the source short-circuit power changes.

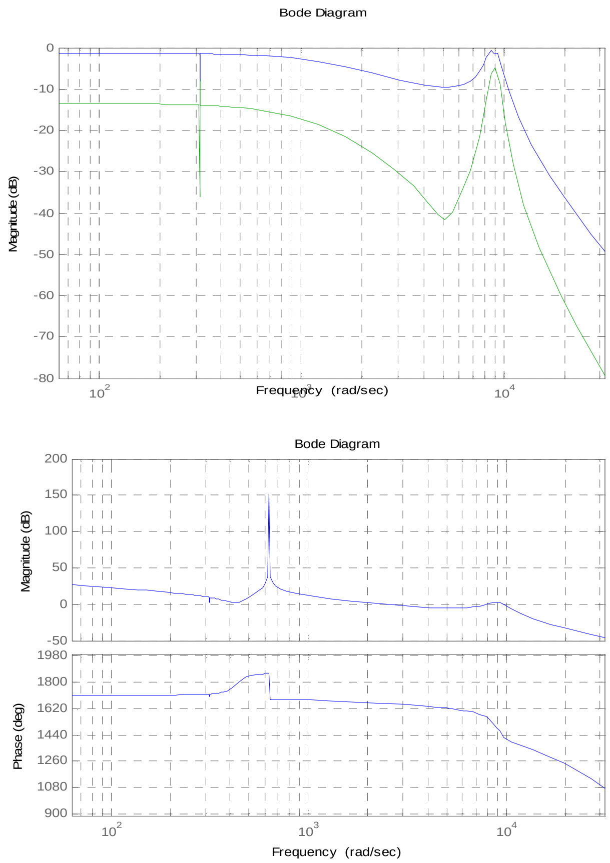


Fig. 3. Frequency Response for SSC system

3. PSO Methodology and Algorithm

In this work, the objective function to obtain the optimal values of K_p and K_i of the PI controller, which lead to the minimum ITSE, is calculated as follows [1]:

$$ITSE_d = \int_0^\infty t \cdot error_d^2 dt \quad (1)$$

$$ITSE_q = \int_0^\infty t \cdot error_q^2 dt \quad (2)$$

$$ITSE = ITSE_d + ITSE_q \quad (3)$$

where $error_d$ and $error_q$ are errors in load voltage of d-component and q-component, respectively.

The objective function to minimize ITSE is determined as follows:

$$Minimize \ \{ \ ITSE(K_p, K_i) \ \} \quad (4)$$

$$\text{subject to} \quad 0 \le K_p \le 100 \ , \ 0 \le K_i \le 10 \quad (5)$$

PSO algorithm used for minimizing ITSE begins by: 1) Create the initial particles and assigning them initial velocities; 2) Evaluate the objective function at each particle location and determine the best (lowest) function value and the best location; 3) Choose new velocities, based on the current velocity, individual best locations for the particles and the best locations of their neighbors; 4) Update iteratively the particle locations (the new location is the old one plus the velocity, modified to keep particles within bounds), velocities, and neighbors.

Iterations proceed until the algorithm reaches a stopping criterion.

For a dimensional search space, the position of particle *p* is given by the following vector:

$$Z_p = (Z_{p1}, Z_{p2}, ..., Z_{pn}) \tag{6}$$

The velocity of particle *p* is given by the following vector:

$$V_p = (V_{p1}, V_{p2}, ..., V_{pn}) \tag{7}$$

with *n* being the number of the swarm particles, V_p the velocity vector of particles and Z_p the position vector of particles.

$$\begin{aligned} &\hat{g}_j \in \{g_0(t_i), g_1(t_i), ... g_n(t_i)\} | obj(\hat{g}(t_i)) \\ &= \min\{obj(g_0(t_i)), obj(g_1(t_i)), ..., obj(g_n(t_i))\} \end{aligned} \tag{8}$$

where:

g_p Personal best position ever found by a particle *p*.

$g_p(t_i)$ Personal best position of particle *p* at the time t_i and it is called (*Pbest*).

$\hat{g}_j$ Global position in which the objective function *obj* achieves its minimum value.

$\hat{g}_j(t_i)$ Global best position ever found by the swarm at time t_i and it is called (*gbest*).

The velocity update of particle p is given by:

$$\begin{aligned} v_{p,j}(t_i+1) = v_{p,j}(t_i) + c_1 \cdot r_{1,j}(t_i) \cdot [g_{p,j}(t_i) - z_{p,j}(t_i)] \\ + c_2 \cdot r_{2,j}(t_i) \cdot [\hat{g}_j(t_i) - z_{p,j}(t_i)] \end{aligned} \tag{9}$$

where:

$z_{p,j}(t_i)$ Position of the particle *j* at time t_i.

$v_{p,j}(t_i)$ Velocity of the particle *j* at time t_i.

$v_{p,j}(t_i+1)$ New velocity of the particle *j* at time t_i+1.

r_1, r_2 Independent random numbers from the interval [0, 1].

c_1, c_2: Acceleration coefficients and equals to 2.

Each particle *p*, because of its velocity, obtains a new position, which depends on its previous position and velocity:

$$z_p(t_i+1) = z_p(t_i) + v_p(t_i+1) \tag{10}$$

where $z_p(t_i+1)$ is the position of the particle *j* at t_i+1.

In the global best model, all the particles of the swarm are defined as a neighbour of a particle *p*. Each particle can be influenced by any of other particles. The presentation of the swarm in this case can be made by a star topology. The equations for $\hat{g}(t_i)$ and $v_{p,j}(t_i)$ of *gbest* model are given by Eqs. (8) and (9) respectively. The PSO algorithm with inertia weight is given by [16]:

$$\begin{aligned} v_{p,j}(t_i+1) = \omega \cdot v_{p,j}(t_i) + c_1 \cdot r_{1,j}(t_i) \cdot [g_{p,j}(t_i) - z_{p,j}(t_i)] \\ + c_2 \cdot r_{2,j}(t_i) \cdot [\hat{g}_j(t_i) - z_{p,j}(t_i)] \end{aligned} \tag{10}$$

where:

$$\omega = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{Iter_{\max}} \times Iter$$

Iter: Iteration number.

$Iter_{max}$: Maximum iteration number.

ω_{max}: Initial weights.

ω_{min}: Final weights.

It was demonstrated that 0.9 for ω_{max} and 0.4 for ω_{min} can greatly improve the performance of PSO [15]. This algorithm runs the Simulink model in each time of evaluating the objective function and the simulation time equals the transient time of the system (0.1 second). The steps of the *gbest* PSO algorithm are applied as follows:

Step 1. Initialization.

Step 2. Velocity and position update.

Step 3. Update of the *pbest* and *gbest*.

Step 4. Go to Step 2 until satisfying stopping criteria which is relative change in the best objective function value *gbest* over the last 20 iterations is less than 1e-99.

The detailed implementation strategies of the *gbest* PSO algorithm are described and the flow chart is presented in the following algorithm.

Load Simulink model, maximum iterations ($Iter_{max}$)=500 and Population size (j) =30.

Initial each particle (K_p, K_i) of population for objective function of Eq. 4.

Initial the personal best position (*Pbest*) for each particle of population.

Evaluate the objective function of Eq. 4 (*ITSE*) for each particle of population.

Set iteration counter $Iter_{max}$=1.

While (stopping criteria does not achieved or $Iter_{max} \leq 500$) ***Do***
  Determine the global best position ever found by the swarm (*gbest*), based on Eq. 8.
  Set iteration counter *j*=1.
While (j≤ 50) ***Do***
  Determine the velocity for each particle of population, based on Eq. 9.
  Determine the new position of particle, based on Eq. 10.
  IF (new position in agreement with the constraints of Eq. 5)
Re-evaluate the objective function of Eq. 4 (*ITSE*), for each particle's new position.
  Update the particle position.
    IF (evaluation of new position < *Pbest*)
    Update best position (*Pbest*).
    END IF
      Set *j*=j+1
    END IF
  End While
      Set $Iter_{max} = Iter_{max}+1$
End While

Determine the global best particle, based on Eq. 8.

4. Application of PSO for SSC

The nonlinearity behaviour of each component in the three-phase voltage regulator's power circuit is considered and implemented in time domain based on the MATLAB Simulink's power system library and is taken as the objective function of Eq. 4. Designed computer programs based on MATLAB programing are prepared to find the optimal tuning parameters of PI controller of three-phase voltage regulator converter based on PSO algorithm.

Constant values of reference load voltage and reference load frequency are set. Optimal parametric values of PI controller for SSC are found by solving the objective function as shown in Fig. 4 based on PSO algorithm. From this figure, it can be seen that the optimal tuning is achieved approximately through 30 iterations to obtain the minimum value for integral of time multiply squared error (ITSE) of 10.6285e-3. The obtained optimal gains of PI controller are K_p =1.48 and K_i =1667 for D, Q, and zero-sequance controller.

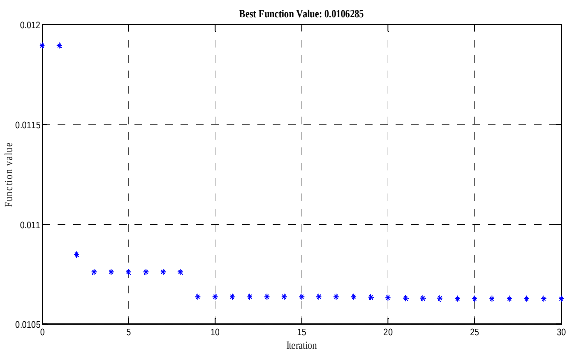


Fig. 4 objective function evaluation

5. Dynamic Simulation Results of SSC based on PSO-PI controller

All simulation parameters are given in the Appendix.

Case1: Single -Phase Fault

Figure 5 presents the simulation results when a phase to ground resistive fault occurs, with a fault resistance equal to 0.0117 Ω. The fault is produced at the high-voltage (HV) side of the distribution transformer. It starts at 20 ms and last for three periods of the fundamental frequency. It is observed that the SSC quickly injects the necessary voltage components to maintain the load voltage. The SSC injected voltage and the load voltage are shown in Figure 5. Per-unit variables are used and nominal powers and nominal phase to phase voltages have been selected as base magnitudes. It is observed that during the fault, the voltage in phase-A at the PCC drops down to 20% of its nominal value, while phase to ground load voltages remain almost constant during the whole event, due to the compensating actions of the SSC. Also, the figure 5 shows the d-q components in rotating reference frame of the load voltage. Moreover, it is clear that the DC voltage is constant with high dynamic performance against the single phase fault.

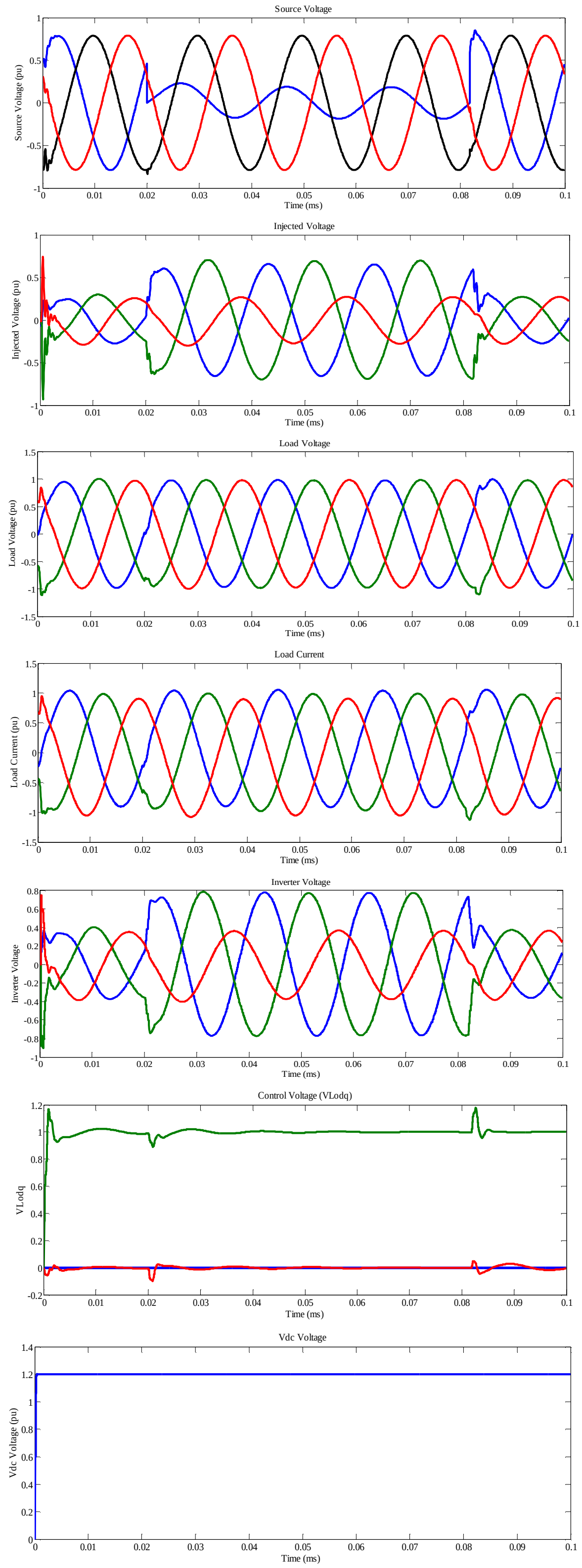


Fig. 5. Compensation of load voltage for SSC (single-phase fault and short circuit power = 20 pu)

Case 2: Double-Phase Fault

Figure 6 presents the simulation results for the SSC system when there is a double -phase fault at the HV-side of the distribution transformer, with a fault resistance of 0.0117 ohm. The source short-circuit power is made equal to 20 pu and no additional load is connected. The voltage sag starts at 20 ms and it is kept until 80 ms.

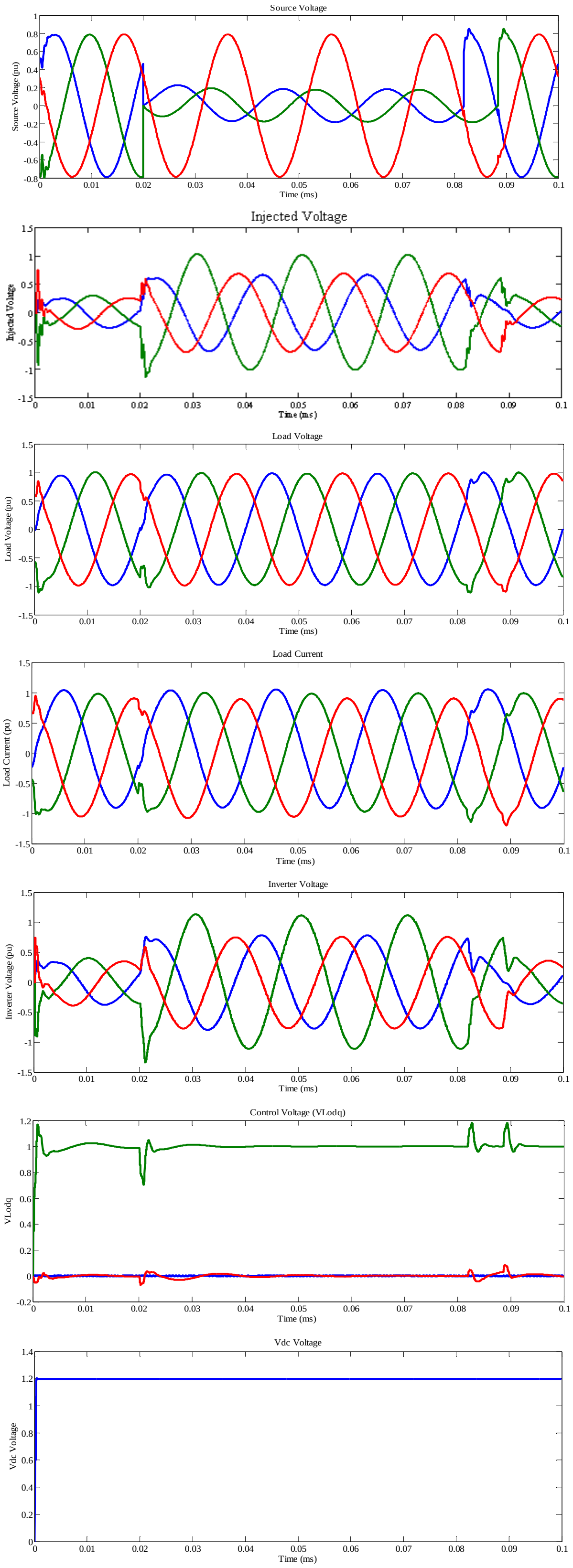
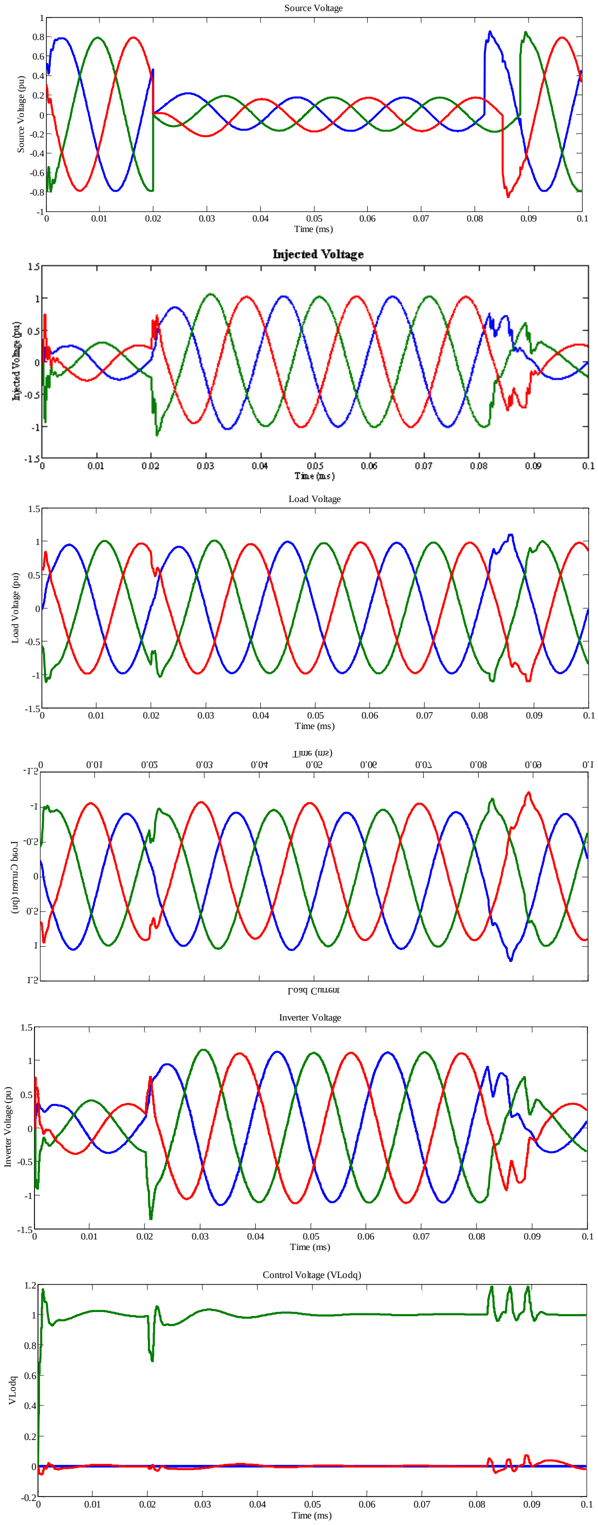


Fig.6. Compensation of load voltage for SSC (Double-phase fault and short circuit power = 20 pu)

Figure 6 shows the voltage generated by the SSC and the compensated load voltage, respectively. As a result of SSC, the load voltage is kept almost constant at 1 pu throughout the simulation. This figure also shows the DC voltage and d-q components of the load voltage.

Case 3: Three - Phase Fault

Figure 7 presents the simulation results for the SSC system when there is a three-phase fault at the HV-side of the distribution transformer, with a fault resistance of 0.0117 ohm. The source short-circuit power is made equal to 20 pu and no additional load was connected. The voltage sag starts at 20 ms and it is kept until 80 ms.



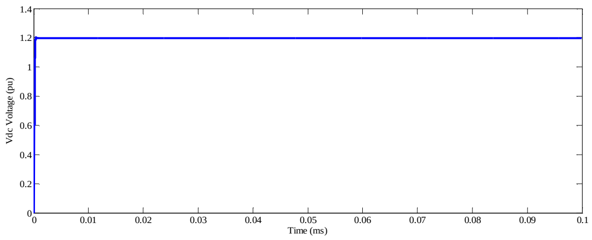


Fig. 7. Compensation of load voltage for SSC (Three-phase fault and short circuit power = 20 pu). Case 3.

Figure 7 shows the voltage generated by the SSC and the compensated load voltage, respectively. As a result of SSC, the load voltage is kept almost constant at 1pu throughout the simulation. Moreover, the figure shows the d-q components of load voltage and the DC voltage.

6. Conclusions

The study presented in this paper has been carried out by using numerical simulation. The simulation results have shown clearly the performance of the SSC for the compensation of voltage sags. The SSC has handled both balanced and unbalanced situations without any difficulties and has injected the appropriate voltage component to correct rapidly any disturbance in the supply voltage to keep the load voltage balanced and constant at the nominal value. Based on the simulation carried out, it is clear that a SSC can tackle voltage sags when protecting sensitive loads. If a voltage supply without zero-component is expected two identical controllers can be used with Park's transformation (one for the d-axis and another for the q-axis). However, a third controller (zero component) is required if situations with zero voltage component in the supply is expected.

Appendix

Parameters of the SSC test system:

- Electrical system viewed from the PCC: Short Circuit Power = 20 pu; Equivalent inductance = 157 μs; Equivalent Resistance = 0.007 pu;
- Distribution transformer and injected transformer: Short Circuit Power = 14 pu; Winding 1 Inductance = Winding 2 Inductance = 185 μs; Winding 1 Resistance = Winding 2 Resistance = 0.023 pu; Magnetizing Inductance = 63.66 s; Magnetizing Resistance = 1500 pu
- Filter Unit : Filter Inductance = 369.5 μs; Filter Capacitance = 55.98 μs-1
- Inverter Circuit: Switching Frequency= 4.95 kHz; Sampling Frequency=9.9 kHz
- Sensitive Load Apparent Power=1 pu; Power Factor = 0.93

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