J Electr Eng Technol.2017; 12(4): 1340-1347
http://doi.org/10.5370/JEET.2017.12.4.1340

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Power Factor Improvement of Distribution System with EV Chargers based on SMC Method for SVC

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Abstract – Utilization of Electric Vehicles (EVs) have been growing popularity in recent years due to increment in fuel price and lack of natural resources. Random unexpected charging by home EV charger in distribution is predicted in the future. The power quality problems such as fluctuation of power factor in a residential distribution network was explored with random EV chargers. This paper proposes a high-performance nonlinear sliding mode controller (SMC) for an EV charging system to compensate voltage distortions and to enhance the power factor against the unbalanced EV chargers. For the verification of the proposed scheme, MATLAB-Simulink simulations are performed on 22.9-kV grid. The results show that the proposed scheme can improve the power factor of a smart grid due to the EV chargers on the grid.

Keywords: Sliding Mode Controller (SMC), Electric Vehicles (EVs), SVC, Unbalanced Load, EV Charger

1. Introduction

Recently, Electric vehicles (EVs) play a vital role in reducing the greenhouse gases coming from the transportation. The increasing utilization of EVs caused additional loads and power quality problems such as unbalancing, fluctuation and reducing of power factor on the power grid. Impacts of a large fleet of EVs are so serious on the distribution system and the peak load of charging is major problem in the power system [1]. For charging EVs, majority of them will utilize home charger when the owners arrive at home afternoon. Simultaneous EV charging could overload the grid.

A lot of research has been conducted to solve the problem of utilizing EVs such as unbalancing of load fluctuating in the grid and overloading of the distribution transformers connected in the power system [2-11]. One of the solutions is SVC which has fast dynamic characteristics that can effectively protect the perturbation of voltage source [12]. When EVs start for charging after connecting to grid, SVC provides an effective way to improve the power factor, power transfer capability, and voltage stability in a power system.

However, compensating the reactive power is necessary. For SVC system to function in the required time in the grid, fixed and automatic power factor correction capacitors are used [13]. Automatic capacitors are also known as switched capacitors and can inject variable reactive power to the grid, whereas fixed capacitors supply a constant kvar.

Physical systems are nonlinear in nature so transmission lines with SVCs have nonlinear characteristics. Many nonlinear controller concepts such as feedback linearization and sliding mode controllers (SMCs) have been investigated and applied for controlling nonlinear system [14-16]. Such systems are controlled using nonlinear control techniques such as SMCs [17]. SMCs can control system uncertainties and external disturbances with good performance [18-20]. The dynamic behavior of the system and the closed-loop response are two main advantages of the SMC method [21, 22]. It has been successfully applied to underwater vehicles [23], automotive transmissions, engines, power systems [14], induction motors [21], robots [20, 24], electric drives [16, 25], the human neuromuscular process [26], and elevator velocity [27]. SMC has also been applied to DC motors in simulations [16, 28, 29]. Also, other concept such as ASRFC has been suggested for controlling nonlinear system which operates in parallel with HVC to achieve the best result in the system. This method is so complex as compared to SMC [30].

In this study, an SMC was designed for an SVC connected to the grid to improve the power factor. The effects of adding the SMC to the system were investigated. The proposed scheme was validated through computer simulations of a 22.9-kV grid.

2. Static VAR Compensator (SVC)

SVCs are used for many different purposes in power

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Received: September 28, 2016; Accepted: March 13, 2017

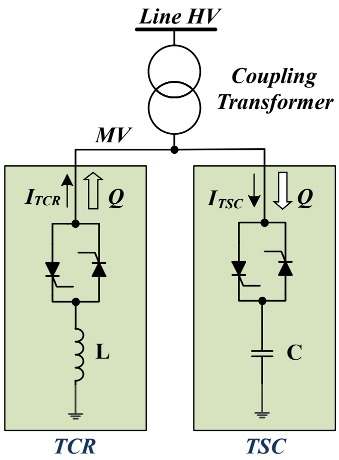


Fig. 1. SVC configuration

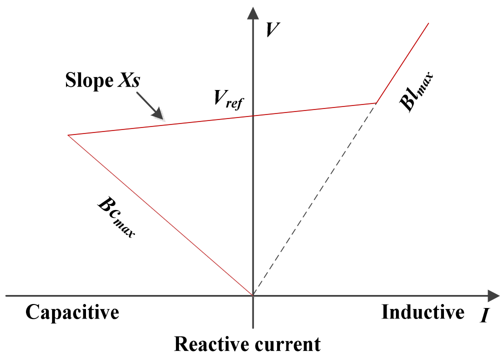


Fig. 2. SVC steady-state control characteristics

systems. The fundamental purpose for SVC is fast controlling of voltage in the weak bus of the power system. SVC probably used in a low-voltage transmission line to compensate voltage, source power factors and unbalance load in the grid. SVCs are connected in shunt with grid that can generate or absorb reactive power with varied outputs and control power factor and source voltage in the smart grid.

A simple SVC has a thyristor switch capacitor and thyristor controlled reactor (TSC-TCR) configuration, as shown in Fig. 1.

For connecting SVC to the AC bus directly in the smart grid to control source voltage and improve power factor, transformer is needed.

2.1 SVC V-I characteristics

For regulation at the voltage reference (V_{ref}), SVC susceptance should be kept between the total reactive power of the capacitor banks (B_{cmax}) and the reactor banks (B_{lmax}). The SVC can be operated in voltage regulation mode or VAR control mode. In voltage regulation mode, the SVC's simplified steady-state control characteristics are shown in Fig. 2.

The V-I characteristics are described by the following three equations:

$$V = V_{ref} + X_s \cdot I \text{ , if SVC is regulation range } -Bc_{max} < B < Bl_{max} \quad (1)$$

$$V = -\frac{1}{Bc_{max}} \text{ , if SVC is fully capacitive } (B = Bc_{max}) \quad (2)$$

$$V = \frac{1}{Bl_{max}} \text{ , if SVC is fully inductive } (B = Bl_{max}) \quad (3)$$

where, V and I are positive sequence voltage, in p.u, and reactive current (I > 0 indicates an inductive current), in p.u/P_{base} and P_{base} is three-phase base power. X_s, B_{cmax}, and B_{lmax} are droop reactance, maximum capacitive susceptance, and maximum inductive susceptance, in p.u/P_{base}.

2.2 SVC dynamic response

Response time of SVC is fast for changing voltage of power system. Voltage regulation depends on proportional gain (K_P) and integral gain (K_i), sag reactance (X_s) and system stability (i.e. short current).

For voltage controller (K_p = 0), firing angle will be neglected when T_m (voltage measurement time) and T_d (average time delay) are constant. Closed-loop system includes SVC and smart grid that can be approximated by a first-order system with the following closed-loop time constant:

$$T_c = \frac{1}{k_i \cdot (X_s + X_n)} \quad (4)$$

where, T_c and K_i are closed loop time constant and proportional gain of the voltage regulator. X_s and X_n are droop reactance and equivalent power system reactance, in p.u./P_{base}. This equation demonstrates that the response is faster when the gain is highly increasing or the system short-circuit level is lower (i.e. higher X_n values).

3. Phase Voltage Analysis of EV Connected to a Grid

Large loads are symmetrical in three-phase power system. Some imbalance in load is caused mainly by electric railways, electric vehicle charger or other single phase load that are utilized in three phase power system.

Imbalance occurs in short-circuit conditions due to incorrect operation of the switching devices, conductor abruptions etc. Voltage and current harmonics cause imbalance in the grid.

The Fortescue method of symmetrical components is used to calculate the unbalanced load-connected phase voltages:

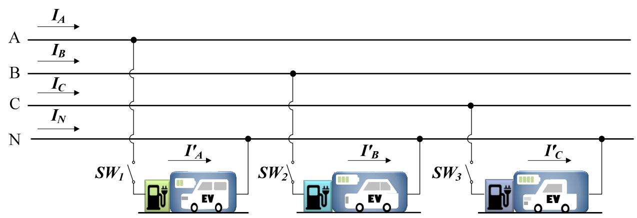


Fig. 3. EVs charging by three single-phase voltages

$$\begin{bmatrix} X_0 \\ X_+ \\ X_- \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} X_A \\ X_B \\ X_C \end{bmatrix} \quad (5)$$

where X_A, X_B, and X_C are unbalanced system phasors and X_0 (zero sequence), X_+ (positive sequence) and X_- (negative sequence) are the phasors of symmetrical components and a=1∠120° is a unit complex operator.

3.1 EVs charging by single-phase voltage

When EVs are charging by single phase voltage source (i.e. $V_{A)}$, that means only SW_1 is ON, as shown in Fig. 3.
The currents in the figure are:

$$I_A \neq 0, I_B = I_C = 0 \quad (6)$$

The symmetrical components of phasors can be obtained by using Eq. (5).

$$\begin{aligned} I_0 &= \frac{1}{3}(I_A + I_B + I_C) = \frac{1}{3} I_A \\ I_+ &= \frac{1}{3}(I_A + aI_B + a^2 I_C) = \frac{1}{3} I_A \\ I_- &= \frac{1}{3}(I_A + a^2 I_B + aI_C) = \frac{1}{3} I_A \end{aligned} \quad (7)$$

The neutral current is obtained by the following equation:

$$I_N = -3I_0 = I_A \quad (8)$$

Due to EV chargers connected to power grid, zero sequence components are discovered in the line, Eq. (7) shows effect of zero sequence current in the grid.

During EVs charging in a single-phase mode of the power grid, an unbalance current is flowing which creates a neutral current, voltage drop as well as distort the voltage balance in the power system [21].

3.2 EVs charging by two single-phase voltages

When EVs are charging by two single phase sources (i.e. V_A and V_B) that means SW_1 and SW_2 are ON.

The currents in the line conductors are:

$$I_A \neq 0, I_B \neq 0, I_C = 0 \quad (9)$$

The phasors of the symmetrical components can again be determined using (5):

$$\begin{aligned} I_0 &= \frac{1}{3}(I_A + I_B + I_C) = \frac{1}{3}(I_A + I_B) \\ I_+ &= \frac{1}{3}(I_A + aI_B + a^2 I_C) = \frac{1}{3}(I_A + aI_B) \\ I_- &= \frac{1}{3}(I_A + a^2 I_B + aI_C) = \frac{1}{3}(I_A + a^2 I_B) \end{aligned} \quad (10)$$

Zero sequence components are also created for two loads connected in this way. The neutral current is obtained by (11):

$$I_N = -3I_0 = -I_A - I_B \quad (11)$$

3.3 EVs charging by three single-phase voltages

When all the three voltage sources are connected (i.e. V_A, V_B and V_C) for charging EVs in Fig. 3. All loads that connected to three-phase are symmetrical and in case of some fault (for a special period of time) are operated asymmetrically.

For this case of EVs charger connected to grid, negative and zero sequence current have values and it is not zero. When EV are charging by grid with sufficient voltages, source voltage remains constant without changing. When voltage source drops in neutral point, phase voltage will shift and neutral point will have current $I_N = -3I_0$. When unbalance voltage drops, the line main voltage at the point of common coupling will be unbalanced.

4. System Description

In the proposed system SVC (that consist of TCR and Three TSC's) is connected to main 22.9-kV bus via a 333-MVA, 22.9/16-kV transformer on the secondary side with X_k=15%, in parallel to the smart grid.

The voltage drop of the regulator is 0.01 p.u/100 VA. Operating point variation of SVC is from fully capacitive to fully inductive. For this simulation SVC voltage varies between 0.97 (=1 - 0.03) p.u and 1.01 (=1 + 0.01) p.u.

5. Modeling of Static VAR Compensator

The SVC provides controllable reactive shunt compensation for dynamic voltage control using high-speed TSC/TCR devices. In general, TCR and TSC are used in

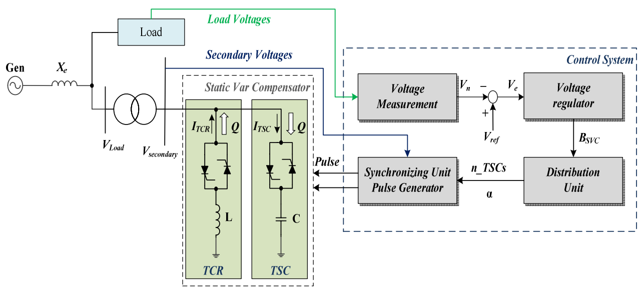
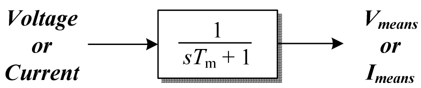
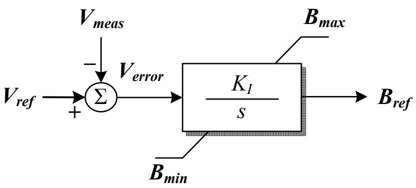


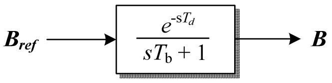
Fig. 4. SVC diagram and control system [30]



(a) Measurement module



(b) Voltage regulator module



(c) Thyristor susceptance control model

Fig. 5. Detailed model of control system

SVC. TSC and TCR have different role in SVC. TSC role is stepped response and TCR role is providing a smooth or continuously variable susceptance. Fig. 4 shows the concept of TCR and TSC of the operating process.

Main duty of SVC is to control and enhance the bus voltage profile.

The characteristics of the measuring and monitoring of filter circuit can be simplified by the transfer function as shown in fig. 5(a). This is integral type of voltage control model.

Fig. 5(b) and Fig. 5(c) show the voltage regulator module and the thyristor susceptance control model.

Where T_d is delay time or (dead time) and T_b is the firing angle of thyristor. The value of delay time can be neglected, because it is approximately equal to 1/12 of the fundamental cycle.

The compensator susceptance, $B_{SVC,}$ is given by:

$$B_{SVC} = \frac{B_0(B_{TSC} + B_{TCR})}{B_0 + B_{TSC} + B_{TCR}} \tag{12}$$

where, B_0 is the susceptance of the transformer [31].

When load is balanced and no EV charger connected in the system for charging, power factor of system is stable

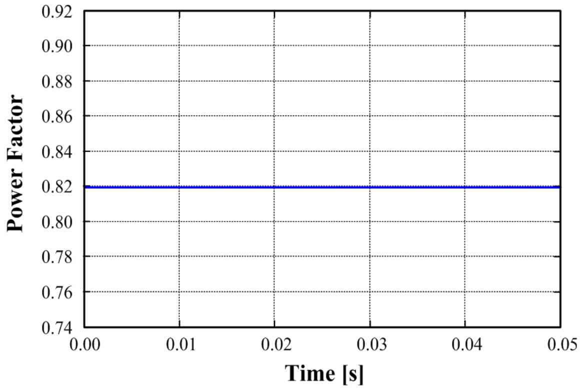


Fig. 6. Power factor of system without EV charger & SVC

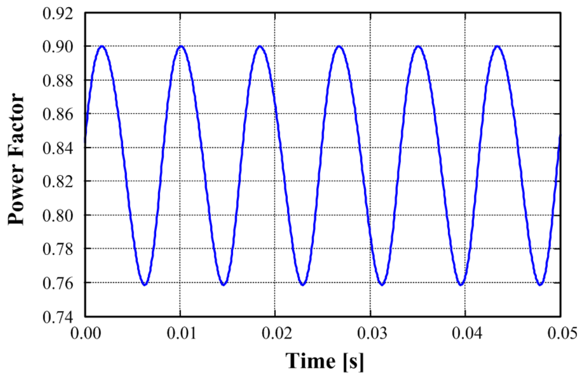


Fig. 7. System power factor during EVs charging without SVC

and no fluctuation occurs. Fig. 6 shows power factor without any EVs are charging in the grid.

When the load changes in the smart grid, power factor also changes. For power factor correction, SVC with controller manages injecting and absorbing reactive power into the grid.

When 1.5 times the normal load is connected to the system, such as an EV (Fig. 3), unbalanced load occurs. Fig. 7 shows system power factor when EVs start charging in grid without SVC.

The mean value of power factor in smart grid which is 0.83 and variation of power factor is 0.14, in Fig. 7. SVC is recommended to improve the power factor. Fig. 8 illustrates that system power factor with SVC at the same condition, and the mean value of power factor in smart grid becomes 0.915, and variation of power factor is 0.09.

Power factor is improved by the SVC. However, the distortion problem from plugging into the EVs has not been solved and proper power factor has not been achieved with this method. For the best power factor, the power factor curve should be unity with no harmonic distortions. For solving this problem, additional controller is needed for SVC system. ASRFC and HVC Methods are introduced in [30]. During ASRFC operation, system power factor is improved, but harmonics are appeared at the same time.

For eliminating harmonics from the ASRFC system, additional controller such as HVC is required. However, these methods are complicated to set up the parameters such as PI controller gains of ASRFC and HVC. In this paper, SMC is therefore suggested for the system. SMC method is simple and widely used to control nonlinear systems as SMC method is not required to use any compensation method.

6. Slide Mode Controller with SVC

SMC is a nonlinear control method that uses the state trajectory on a sliding surface to make the system output converge to a desired output based on the desired dynamics [32-34]. The control rules in the SMC have two stages, as shown in Fig. 9.

As the sliding surface becomes stable (i.e., $\lim_{t\to 0} e(t) = 0$), the error asymptotically approaches zero as time goes to infinity [35].

The dynamic equation for the nonlinear system is given below:

$$X^{(n)} = f(x) + b(x)u(t) + d(t) \tag{13}$$

where f(x) and b(x) denote the uncertain nonlinear functions with known uncertainty, and d(t) is the disturbance that enters the system. The error state vector with desired state vector $X_d(t)$ is:

$$\tilde{X} = X(t) - X_d(t) \tag{14}$$

An appropriate sliding surface (which is also called a switching function) must be defined in the state space in the design of the SMC. This sliding surface has the following form:

$$s(t) = (\lambda + \frac{d}{dt})^{(n-1)} \tilde{X}(t) \tag{15}$$

where n is the order of the uncontrolled system and λ is a positive real coefficient. Secondly, the control law to adjust the system to the selected sliding surface must be designated.

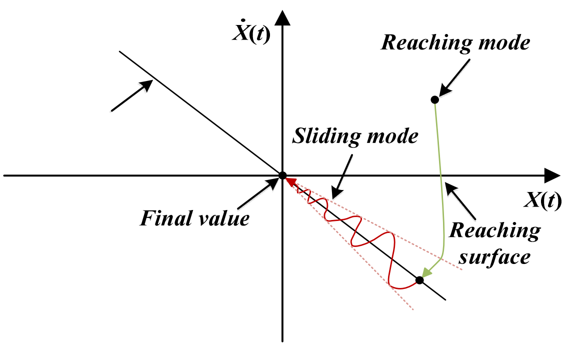


Fig. 9. Phase plane of SMC

Table 1. Power factor variation in the power system when EVs are charging by grid

	Without SVC	With SVC	SVC with SMC
Average of power factor [%]	83	91.5	99
Interval of upper and lower of power factor [%]	14	9	1.5

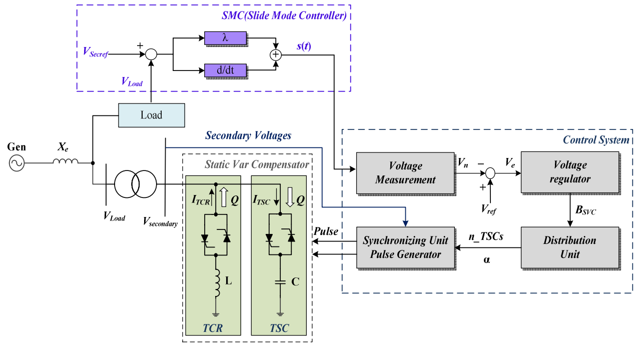


Fig. 10. Block diagram of the SMC with SVC connected to the grid

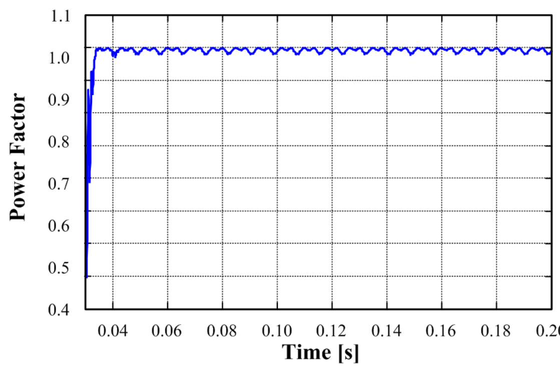


Fig. 11. Power factor of the grid with SVC & SMC

Fig. 10 shows a block diagram of the SMC with the SVC connected to the grid.

Fig. 11 shows Power factor of the grid with SMC. After using the SMC in the SVC, power factor of system became to 0.99.

Table 1 shows the interval of system of power factor when EVs are starting for charging for different conditions of the SVC and controllers.

As shown in Table 1, power factor of system is almost 83% and fluctuation is around 14% without SVC. This condition is not feasible for stability of smart grid. Step-up SVC with conventional method improves power factor up to 91.5% and reduces its variation from 14% to 9%. For getting unity power factor, SMC method is suggested to the SVC which improves the power factor up to 99% and reduces its variation from 14% to 1.5%.

7. Conclusion

Charging EV by grid decreases source power factor and makes it unstable. In this paper, SVC with a sliding mode controller to improve the power quality of the smart grid connected with EV chargers is presented. The main disadvantage of conventional methods such as ASRFC/HVC is that the controller is complex and too hard to set up the parameters such as PI gains in the controller. A new SVC technique based on SMC is proposed in this paper which can improve the power factor without harmonic compensator. The principles of the SVC without SMC and proposed SVC with SMC are modeled and analyzed in MATLAB/Simulink. The simulation results successfully show that power factor has been improved.

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