Improvement of power factor in smart grid connected with EV charger and optimal sizing of SVC capacitor using SMC

Saeid Gholami Farkoush, Chang-Hwan Kim, Abdul Wadood, Tahir Khurshaid, Kumail Hassan Kharal, Sang-Bong Rhee

Abstract - **Electric vehicles (EVs) have a main role in reducing the emission of greenhouse gases in the world. In addition, EVs will have greater share in future transportation systems, which will cause an additional load on the electric grid. The Slide Mode Controller (SMC) topology is used for the improvement of the power factor in distribution system, for example, home appliance charger and EVs charger station. Power factor is diminished in distributed system by connecting EVs to the system. For solving this problem, Static Var Compensator (SVC) is employed to the smart grid. For reducing the size of SVC and making the power factor more stabilized in smart grid, SMC is suggested. This paper presents size of SVC capacitor investigated with and without using SMC through computer simulations of a 22.9-kv grid.**

Keywords: **Electric vehicles, Smart grid Static Var Compensator, Slide Mode Controller, Capacitor.**

I. INTROUDUCTION

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. In the power system, all power equipment and industrial inductive loads draw reactive power. Increasing the amount of reactive power have enormous impact on the power systems such as generating units, lines, circuit breakers, transformers, relays and isolators. High reactive power increased the size and cost of equipment, also reduced the efficiency of the power system [2]. In distributed systems, the voltage at the load reduces due to lack of reactive power [3].

In addition reactive load will be lower the maximum real power capacity of generator, losses and excessive voltage sags. In such cases, local VAR support suggested using shunt capacitors; that called reactive power compensation. More common compensation methods added to capacitor banks of the system [3]-[4].

Shunt compensation is widely used to improve power factor and voltage stability.

Shunt compensation are almost same with series compensation, with the difference that, they inject current to power system at the point where they are connected. Static Synchronous Generator (SSG) and Static Var Compensator (SVC) can cited for shunt compensation.

The SVC is an important component of a flexible AC transmission system. It provides an effective approach to correct and increase the power factor, enhance voltage stability, and increase the power transfer capability when an unbalanced load happens in the power system for example, when an EV connected to the grid for charging.

The SVC has fast dynamic characteristics that can support the effective system voltage following disturbances. Keeping a reactive power reserve in an SVC during steady-state operation always needed to satisfy the reactive power requirements during system dynamics [5]. In the SVC topologies, there are two types of capacitors for power factor correction: fixed and automatic. Automatic capacitors are also known as switched capacitors. They vary the amount of correction (KVAR) supplied to an electrical system, while fixed capacitors supply a constant KVAR.

In this area, one concept that has been proposed to control SVCs is a delta-connected TCR-FC using a PID controller for power factor correction. However, a PID controller is complicated in comparison to a PI controller in a power system. Also, in an SVC [TCR-FC] system, a capacitor is constant in the system, and controlling the capacitor value is impossible, so it is not a good idea for achieving the best power factor correction [6]. Using an automatic capacitor to achieve the best power factor in the grid is recommended because it is very flexible for any loads that change in the grid.

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The basis for the algorithm that is used in this paper to calculate the compensation susceptances associated with each phase of a delta connected three-phase SVC for power factor correction [7]. A fuzzy logic SVC for power factor correction was presented by Mokhtariet al. [8]. This method is one of the best and most successful techniques among expert control strategies. It is an important tool to control nonlinear, complex, vague, and ill-defined systems, but it is slower than when a PI controller that is used for SVC.

Different approaches have been proposed to diminish the voltage distortion in loads when EVs are connected with a PCC. A selected harmonic compensation method that uses the discrete Fourier transforms (DFT) and Asymmetric Synchronous Reference Frame Controller (ASRFC) has been proposed [9]. However, the DFT method requires too much computation and it is not feasible. In addition, using the SRFC requires knowledge of the leading angle, which compensates for the system delay.

It is well known that physical systems are nonlinear in nature. Nonlinear control design methods such as feedback linearization and sliding mode controllers (SMCs) have been proven as sound and successful methods in control problems [10–12]. Transmission lines with SVCs have nonlinear characteristics. Such systems are controlled using nonlinear control techniques such as SMCs [13]. SMCs can control system uncertainties and external disturbances with good performance [14–16]. The dynamic behavior of the system and the closed-loop response are two main advantages of the SMC method [17-19]. It has been successfully applied to underwater vehicles [20], automotive transmissions, engines, power systems [10], induction motors [17], robots [16, 18], electric drives [12, 21], the human neuromuscular process [22], and elevator velocity [23]. SMC has also been applied to DC motors in simulations [12, 24, 25].
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.

II. STATIC VAR COMPENSATOR (SVC)

Static VAR systems are applied by utilities in transmission applications for several purposes. The primary purpose is usually the rapid control of voltage at weak points in a network. Installations may be at the midpoint of transmission interconnections or at the line ends for compensation of irregular load, voltage, and source power factors in the power system. SVCs are shunt connected static generators/absorbers whose outputs are varied to control the voltage and power factor of the electric power systems. In its simple form, an SVC is connected as a thyristor switch capacitor-thyristor controlled reactor (TSC-TCR) configuration, as shown in Fig. 1. The SVC is connected to a coupling transformer that is connected directly to the AC bus whose voltage/power factor source is to be regulated.

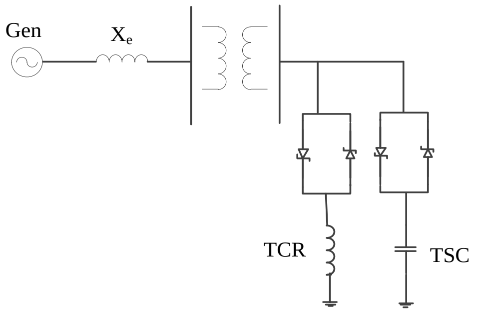

Fig. 1. Configuration of SVC

A. SVC (V-I) Characteristics

The SVC can be operated in two different modes: voltage regulation mode (where the voltage is regulated within limits as explained below) and VAR control mode (where the SVC susceptance is kept constant). When the SVC is operated in voltage regulation mode, it implements the following V-I characteristics. SVC steady-state control characteristics in its simple form are shown in Fig. 2. As long as the SVC susceptance B stays within the maximum and minimum susceptance values imposed by the total reactive power of capacitor banks (Bcmax) and reactor banks (Blmax), the voltage is regulated at the reference voltage Vref. However, a voltage drop is normally used (usually between 1% and 4% of the maximum reactive power output), and the V-I characteristic curve has the slope indicated in Fig. 2. [9].

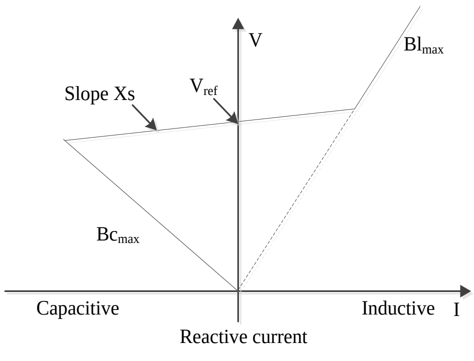

Fig. 2. SVC steady-state control characteristics.

The V-I characteristic is described by the following three equations:

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

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

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

where

V: Positive sequence voltage (p.u.)

I: Reactive current (p.u./Pbase) (I > 0 indicates an inductive current)

X_s: Slope or droop reactance (p.u./Pbase)

B_{cmax}: Maximum capacitive susceptance (p.u./Pbase) with all TSCs in service, no TSR or TCR

B_{lmax}: Maximum inductive susceptance (p.u./Pbase) with all TSRs in service or TCRs at full conduction, no TSC

P_{base}: Three-phase base power specified in the block dialog box

B. SVC Dynamic Response

When the SVC is operating in voltage regulation mode, its response speed for a change of system voltage depends on the voltage regulator gains (proportional gain K_p and integral gain K_i), the droop reactance X_s, and the system strength (short-circuit level). For an integral-type voltage regulator ($K_p = 0$), if the voltage measurement time constant Tm and the average time delay T_d due to valve firing are neglected, the closed-loop system consisting of the SVC and the power system can be approximated by a first-order system with the following closed-loop time constant:

$$T_c = \frac{1}{K_i \cdot (X_s + X_n)} \tag{4}$$

where

T_c: Closed loop time constant

K_i: Proportional gain of the voltage regulator

X_s: Slope reactance p.u./Pbase

X_n: Equivalent power system reactance (p.u./Pbase)

This equation demonstrates that the response is faster when the gain is increased or when the system short-circuit level decreases (higher X_n values) [9].

III. DESCRIPTION OF SYSTEM

This fundamental network used for this paper is IEEE 14-node test feeder [26], as shown in Fig. 3. The network is downscaled from 22.9 kV to 230 V based on the Korea standard so this grid topology shows residential fundamental network. Each node is connected to residential load and some nodes choose randomly for charging EVs.

Assume that an SVC comprising one TCR bank and three TSC banks is connected to a 22.9-kV bus via a 333-MVA, 22.9/16-kV transformer on the secondary side with X_k = 15%. The voltage drop of the regulator is 0.01pu/100VA (0.03Pu/300 VA). When the SVC operating point changes from fully capacitive to fully inductive, the SVC voltage varies between 1 - 0.03 = 0.97 pu and 1 + 0.01 = 1.01 pu.

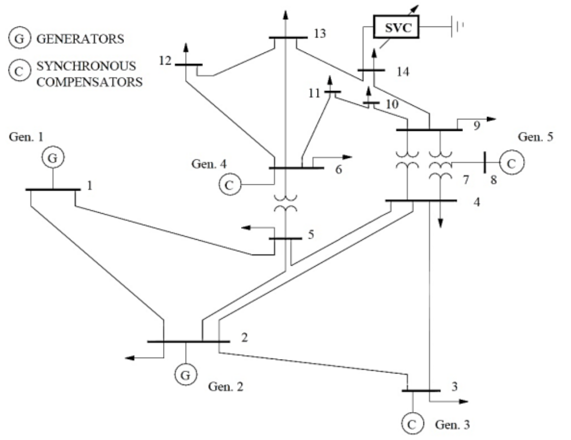

Fig. 3. IEEE 14-node test feeder

IV. MODELLING OF STATIC VAR COMPENSATOR IN POWER SYSTEM STUDIES

The SVC provides an excellent source of rapidly controllable reactive shunt compensation for dynamic voltage control through its utilization of high-speed thyristor switching/controlled reactive devices. In general, the concepts of TCRs and TSCs are used in SVCs. The TSC provides a "stepped" response, and the TCR provides a "smooth" or continuously variable susceptance. Fig. 4. Illustrates a TCR/TSC including the operating process concept.

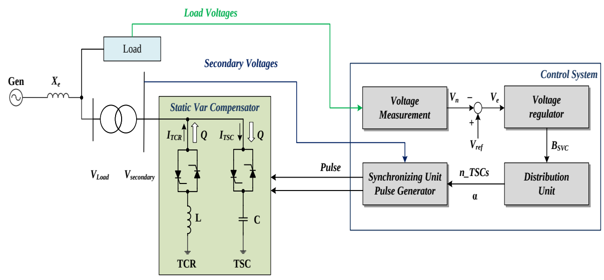

Fig. 4. Single-line diagram of SVC and control system

The control objective of the SVC is to maintain the desired voltage in a high voltage bus. In steady state, the SVC will provide some steady-state control of the voltage to impound it the highest condition at a pre-defined level. When the load is changed in the power system, the power factor is decreased. For improvement of the power factor, the SVC will inject reactive power into the system (within its control limits) to increase the power factor of the system [9].

When 1.5 times the load is connected between A-phase, like when EVs are plugged into the system, it causes an unbalanced load.

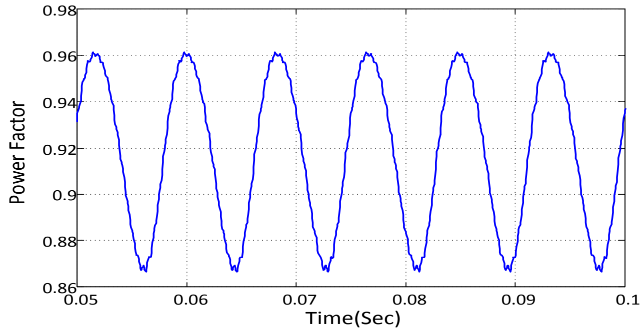

Fig. 5. Power factor of the system when EVs are plugged into the grid with SVC

Fig. 5. Illustrates the power factor of the system when EVs are plugged into the grid with an SVC.

As can be seen in Figure 5, the average power factor of the system is 0.915 or 91.5%, and the upper and lower distortion in the power factor curve is 0.09 or 9%. The problem of distortion occurring in the power factor because of plugging EVs into the system has not been solved [9]. For solving this problem Slide Mode Controller is suggested.

V. 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 [27, 28]. The control rules in the SMC have two stages, as shown in Fig. 6.

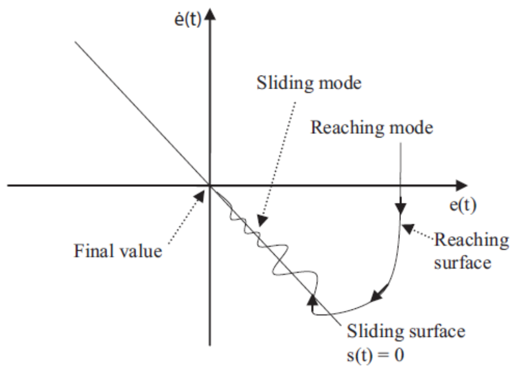

Fig. 6. Phase plane of SMC [29]

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 [30]. The dynamic equation for the nonlinear system is given below:

$$X^{(n)} = f(x) + b(x)u(t) + d(t) \quad (5)$$

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:

$$\tilde{X} = X(t) - X_d(t) \quad (6)$$

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:

$$s(t) = (\lambda + \frac{d}{dt})^{(n-1)} \tilde{X}(t) \quad (7)$$

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

SMC in compared ASRFC and HVC Method is fast and more reliable. Also in ASRFC method for compensation harmonic in system after improvement power factor is needed to utilize HVC. In SMC method don't require to use any compensation method. In addition SMC is not complicated in comparison ASRFC [9].

Fig. 7. Shows a block diagram of the SMC with an SVC connected to the grid.

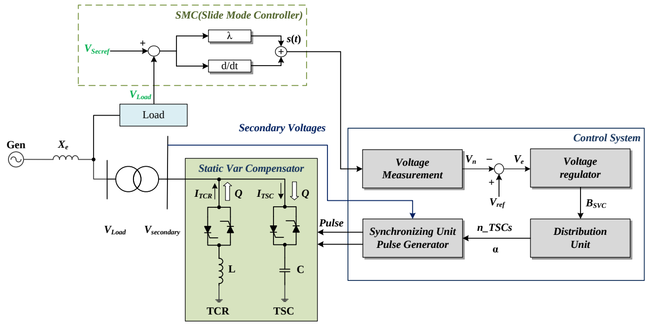

Fig. 7. Block diagram of the SMC with SVC connected to the grid

After using the SMC in the SVC, the power factor of the system is improved to 0.99. Fig. 8. illustrates Power factor of the grid with SMC.

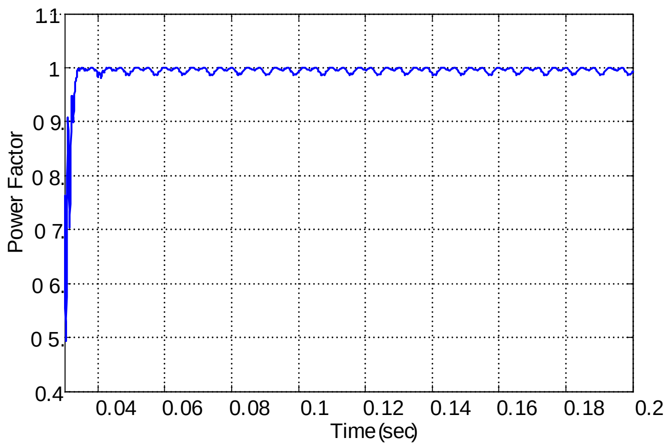

Fig. 8. Power factor of the grid with SMC

Table 1 show the intervals of the power factor in the system when EVs are connected to the grid for different conditions of the SVC and size of SVC capacitor with SMC.

As can see Table 1, Step-up SVC with conventional method improve power factor to 91.5% and reduce Interval of upper and lower of power factor to 9%. For getting unity power factor SMC method suggested to the SVC. With applying SMC, power factor improve around 99% and reduce Interval of upper and lower of power factor to 1.5%. Also after applying SMC in the SVC, size of C_{SVC} is reduced from $30\mu F$ to $6\mu F$.

Table 1: Intervals of the power factor in the system when EVs are connected to the grid for different conditions of the SVC and size of SVC capacitor with SMC.

	SVC	SVC with SMC
Average of power factor (%)	91.5	99
Interval of upper and lower of power factor (%)	9	1.5
C_{SVC}	$30\mu F$	$6\mu F$

VI. CONCLUSION

This paper has presented a sliding mode controller for EV chargers with an SVC connected to the grid. The proposed SMC was used to improve the power factor of the system. Connecting an EV charger to the grid decreases the power factor of the system and makes it unstable, but applying the SMC to the SVC improves the power factor and stability. The SMC increased the power factor from 0.83 to 0.99. With applying SMC in the SVC system, capacitor size of SVC is reduced from 30μF to 6μF. The proposed controller produces excellent results compared to the conventional methods.

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