Flexible Alternating Current Transmission System Devices Compensator for Distribution System

JERNEJA BOGOVIČ & RAFAEL MIHALIČ

Abstract One of the possible solutions for improving voltage conditions in an electric power system (EPS) is applying power electronics based or so called flexible alternating current transmission system (FACTS) devices. However, the appropriate inclusion of a FACTS device into the EPS is not a straightforward procedure. On the contrary, it requires several steps. One of the first steps is the power flow analysis, which requires an appropriate FACTS device modelling.

In the past the models of FACTS devices for Newton-Raphson (NR) power-flow and current-injection calculation methods have been developed. The NR analysis, however, is not always suitable for distribution networks due to convergence problems. This is why new three-phase models of FACTS devices for the forward/backward sweep method are presented in this paper. Their application is demonstrated on an IEEE 34 and 123 bus test systems, in order to clearly present the approach virtues for FACTS modelling in distribution networks with included distributed generation units (DGs).

Keywords: • model • regulator • distribution system • voltage conditions • power flow • FACTS •

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1 Introduction

Voltage and reactive power control in accordance with minimum standards are one of several system services and are an important part of safe, reliable and efficient operation of an electric power system (EPS). One of possibilities for active voltage and reactive power control is including power-electronics-based or so called flexible alternating current transmission system (FACTS) devices into a power network [1]. In this paper application of a three-phase static synchronous series compensator (SSSC) for a voltage control in a steady-state operation of a distribution system is demonstrated. This particular device has been chosen, because in the past it was known for some difficulties with convergence in power-flow calculations [2]. It turned out that even with the multi-parameter devices, for which the synonym is a unified power flow controller (UPFC), are less problematic regarding convergence as SSSC. Therefore even new approaches had to be developed (the so called current approach). The similar logic is followed in this paper, i.e. "if SSSC converges well" also other devices will. Authors are aware that FACTS devices are not often used in the distribution systems, however it is imaginable that in the future SmartGrids concept may play an important role.

The impact of SSSC on power flows has to be considered, regardless of the reason why it is included in the EPS. For that reason an appropriate model of SSSC for power-flow calculations is needed. Numerous models of SSSC for steady state can be found in the available literature [2–5]. They can be divided on current and voltage based models the later having difficulties with convergence. But still most of them are appropriate for Newton-Raphson (NR) power-flow calculation method. However, EPS's with a high R/X ratio may create ill-conditioned problems for the NR (or Newton-type) power-flow algorithms [6] and consequently seriously affecting method's convergence [7]. As this makes the NR method inappropriate for this kind of EPS, the same goes for mentioned SSSC models. As a result, in order to perform power-flow calculations in a distribution system, an efficient and robust method should be used, such as backward/forward sweep method.

The backward/forward sweep methods are most commonly used methods for power-flow calculations in radial distribution networks because they take advantage of a natural feature of the radial networks, i.e. a unique path from any given bus to the source. The basic principle consists of two basic steps: forward sweep and backward sweep. The forward sweep is based on a voltage-drop calculation caused by the current flow via impedance elements from the sending end to the far end of a feeder. The backward sweep on the other hand is based on a calculation of the node injected current and it summation in the opposite direction, i.e. from the far end of the feeder to the sending end [8]. Its advantage is its simplicity in understanding and use; however its disadvantage is applicability limited to radial systems.

Several modifications of backward/forward sweep methods have been created since the first proposal. They made the method suitable also for solving systems with a weakly meshed topology, systems with voltage dependent loads, systems with DG and three-phase systems (also three-phase four-wire systems, including neutral grounding [6]). In this paper a modification of a backward/forward sweep method from [9] is used, with a supplement of DG [10] for testing a new three-phase model of SSSC. Despite conclusions from [11], where model is based on the minimization of the inverter capacity function due to injected voltage, approach in this paper includes the connection of transformer to the EPS as well.

A new three-phase model of SSSC is presented with a task of improving voltage condition in a radial network with included DG. The model is suitable for use in radial network power-flow calculations with forward/backward sweep method. The paper is structured as follows. In section 2 SSSC model is presented, in section 3 the performed power-flow calculations and accompanying results are presented and finally, with respect to applied test system, the conclusions are drawn in section 4.

2 SSSC model

SSSC is a series FACTS device, which consists of an AC/DC converter with a capacitor, which is connected to the EPS via series transformer or transformers (see Figure 19.1). In some cases the capacitor is replaced with a power source. SSSC is capable of controlling active or reactive power-flow at the line, injected voltage magnitude, bus voltage magnitude and impedance (reactance) in meshed systems [12]. However, in radial systems these functions are limited only to injected voltage magnitude and bus voltage magnitude, whereas only the second ability seems reasonable to exploit.

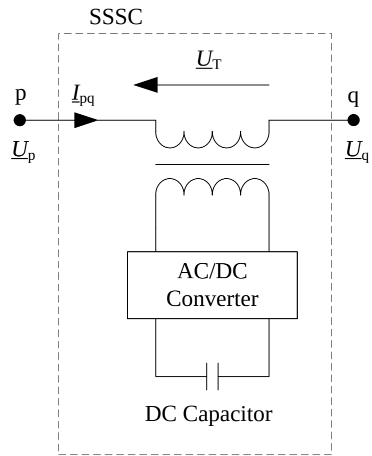

Figure 19.1: Scheme of SSSC

As it was already mentioned, different kinds of SSSC models for power-flow calculations were developed in the past. However, with respect to NR method, they can be treated as unsuitable, as they cause serious convergence issues in radial systems with high R/X ratio. Nevertheless, existing equations can be modified to fit the purpose of forward/backward sweep method. The concept from [2], where the SSSC is presented with a voltage source and a series impedance (mathematical representation of the losses) has been taken as the starting point. This kind concept is the most suitable to use with backward/forward sweep method because of the existence of an additional node (denoted with letter "S") between the impedance and the voltage source (see Figure 19.2).

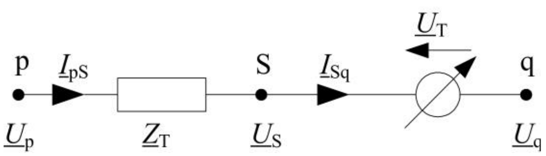

Figure 19.2: Current-based SSSC model

To ensure mathematical correctness of the current-based SSSC device representation, its controllable variables must fulfil some requirements, related to the active-power balance equations, transformer winding connection and the controlled parameters. The numbers of free parameters of controllable variables depend on the implementation of SSSC into EPS. Due to the lack of energy source in the converter DC side, the active-power supplied by the inverter to the system is zero. If SSSC has common DC part for all three-phases the active-power balance equation for SSSC refers to all three-phases (1). If each phase has its own DC part, the active-power balance equations refer to each phase separately (2).

$$\sum_{p=a,b,c} P_{SSSC}^{p} = 0 \tag{1}$$

$$P_{SSSC}^{a} = P_{SSSC}^{b} = P_{SSSC}^{c} = 0 \tag{2}$$

where P_{SSSC}^{p} represents SSSC injected active-power in phase p.

Besides DC part performance, the number of free parameters depends on implementation of the series transformer. If it is Y-connected there is no restriction regarding injected voltage at each phase. For Δ-connection (most appropriate for unsymmetrically loaded EPS) on the other hand, there is a limitation about injected voltage for real and imaginary part (3).

$$\sum_{p=a,b,c} \underline{U}_{SSSC}^{p} = 0 \tag{3}$$

where $\underline{U}_{SSSC}^{p}$ represents injected voltage of SSSC for each phase p.

In accordance with all previously mentioned dependencies due to implementation of SSSC, the controlled parameters refer to all three-phases or are limited to only one phase. The already mentioned SSSC controlled parameters are mathematically described with (4) for injected voltage, (5) for injected reactive power and (6) for nodal voltage.

$$U_{inj}^{p} = U_{inj,ref}^{p} \tag{4}$$

$$Q_{inj}^{p} = Q_{inj,ref}^{p} \tag{5}$$

$$U_{node}^{p} = U_{node}^{p} \tag{6}$$

For independent SSSC-based control of variables, where each SSSC phase has its own DC part regardless of the winding connection of the series transformer, the derivation of equations is rather straightforward. But for SSSC with a common DC part and Δ-connected series transformer, the procedure is more complex. For that reason a new modification of backward/forward sweep method is required, which is presented in continuation. The modification involves quasi-Newton method to solve the system of equations representing SSSC.

3 Results

The three-phase model of SSSC was tested on two different EPS test systems listed below. In all of them the SSSC with common DC part and Δ connected series transformer is used. The power flow was calculated by Matlab and the implemented function *fsolve* was used to detail SSSC. For representation of DG PQ model is used as in [11].

3.1 IEEE 34-bus test system

The IEEE 34-bus test system is an actual feeder located in Arizona, US. In the presented case, two SSSC devices are connected to the IEEE 34-bus test system, the first is placed between nodes 814 and 850 and the second between 852 and 832. The reader should note that initially the voltage controllers are integrated. The DG (photovoltaic (PV) power plant) is connected to the feeder in node 890 and it injects maximum 220 kW of active-power per phase.

Three different situations were tested. The first situation is the basic situation, where two voltage controllers and two shunt capacitors are included into the model. In the second situation the voltage controllers are replaced with two SSSC devices and shunt capacitors are disconnected. In the third situation controllers are replaced with SSSC devices, shunt capacitors are disconnected and DG produces the maximum installed power of 220 kW per phase. To observe impact of SSSC on convergence power-flow calculations were performed for different kW generation of a DG unit ranging from 0 kW up to 220 kW by step of 10 kW.

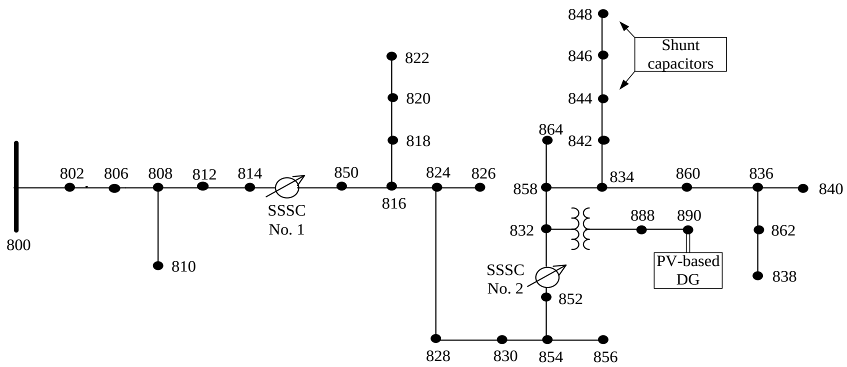

Figure 19.3: IEEE 34-bus test system

Figure 19.4 shows the results of a voltage profile at phase L1 throughout the test system for all three situations. With the solid black line the results for basic situation are shown. With solid grey line the results for the second situation and with dashed grey line the results for the third situation are shown. The voltage profile is most favourable with SSSC units and included DG. In case when DG does not produce any power the voltage profile is still better compared to the basic case although the shunt capacitors are disconnected.

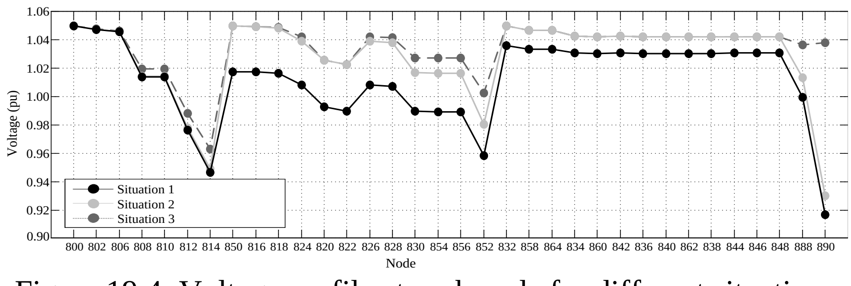

Figure 19.4: Voltage profile at each node for different situations

Figure 19.5 presents the number of iterations needed to achieve the desired mismatch of ε = 10-6 pu between voltage differences in two subsequent iterations. The desired mismatch was achieved in nine iterations for situation 3, which equals to the number of iterations in the basic situation. The number of iterations to achieve desired mismatch is much larger if the DG does not produce any power.

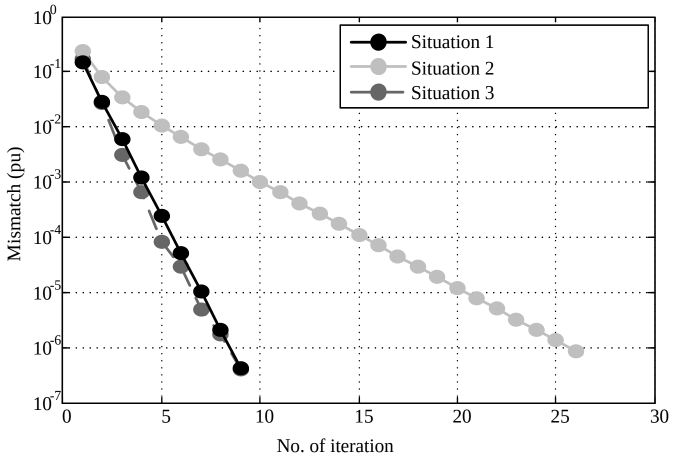

Figure 19.5: Mismatch for IEEE 34-bus test system for different situations

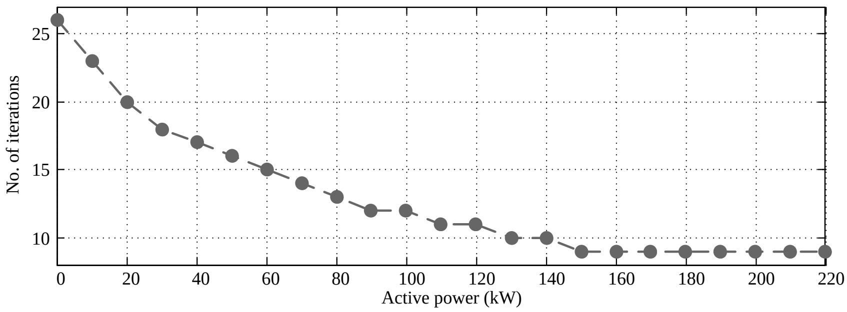

Figure 19.6: Number of iterations for different production of DG with included SSSCs into the feeder

Figure 19.6 illustrates the number of iterations for different injected amounts of DG active-power. The number of required iterations decreases with increasing generation. Although a SSSC device is known for its problems with convergence, the proposed model shows no sign of convergency problems in all tested situations for 34-node test feeder.

3.2 IEEE 123-bus test system

IEEE 123-bus test system is one of the largest test feeders that presents distribution system. In test system two SSSC devices are included. The first is placed between nodes 150 and 149 and the second between nodes 160 and 67. Initially the voltage controllers are integrated.

The DG unit (PV power plant) is included into the system at node 151 and injects maximum 300 kW of active-power per phase. As in previous test example, three different situations are observed: the basic situation, situation No. 2 with included SSSCs and situation No. 3 with included SSSCs and DG at maximum production. As in section 3.1 shunt capacitors are disconnected if SSSCs are installed.

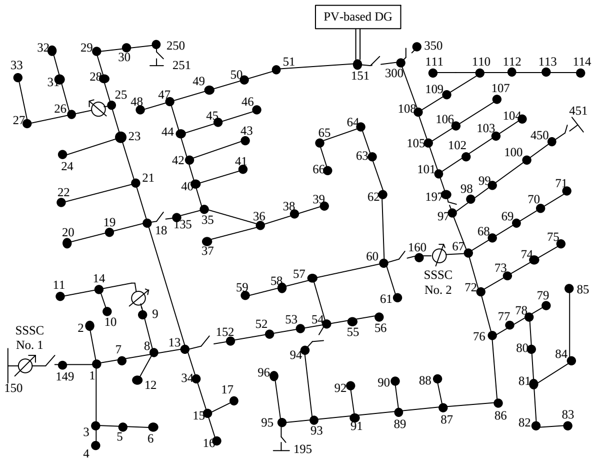

Figure 19.7: IEEE 123-bus test system

Figure 19.8 illustrates the voltage mismatch for three different situations. The desired mismatch is achieved in six iterations if the voltage controllers and shunt capacitors are included in the EPS. Insignificantly more iterations of voltage controllers and shunt capacitors are replaced by SSSCs. Figure 19.9 presents the number of iterations needed to achieve desired mismatch and is almost the same regardless of the production of a DG unit.

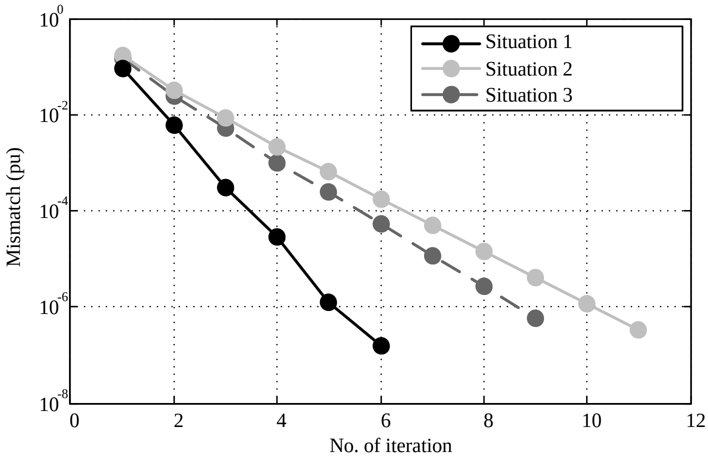

Figure 19.8: Mismatch for IEEE 123-bus test system for different situations

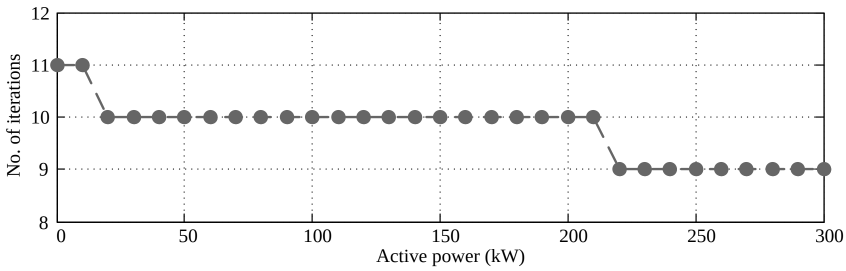

Figure 19.9: Number of iterations for different production of DG with included SSSCs into the feeder

Figure 19.10 shows the injected voltage for both SSSCs for different DG generation. The black line represents the injected voltage at first SSSC (between nodes 150 and 149) and the grey line illustrates the injected voltage at second SSSC (between nodes 160 and 67). The values of injected voltage are around 10 % of rated voltage.

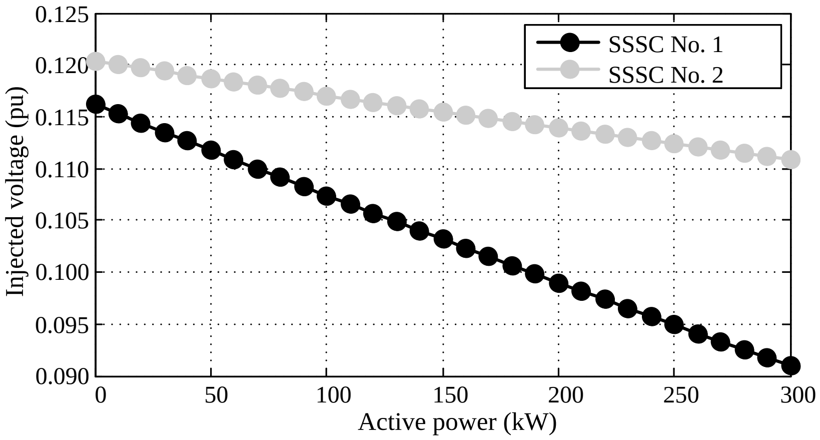

Figure 19.10: Injected voltage of SSSCs for different production of DG

4 Conclusion

The new model of SSSC for nodal voltage control is presented in this paper. The model is tested on two different test-systems; IEEE 34-bus test system and IEEE 123-bus test system for two different situations. The third situation involves DG with maximal power output and the second situation with no DG contribution. Power-flow calculations for different DG production with included SSSC were performed to observe for possible convergency issues.

The results show that the SSSC-based voltage control invokes better voltage conditions with respect to the base case with active controllers. The number of required iterations is in most cases the same if the SSSC or voltage controllers are included in the system even though SSSC is known to have convergency issues in power-flow calculations.

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