MODEL OF STATIC SYNCHRONOUS SERIES COMPENSATOR

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ABSTRACT

This paper presents a model of Static Synchronous Series Compensators (SSSC) for load-flow calculations in a distribution system for the forward-sweep algorithm. The model of SSSC for forward-sweep algorithm is based on current model used in Newton-Raphson load-flow calculations. The model is modified that is used for forward-sweep algorithm, but all known properties are preserved. Since the distribution networks are mainly radial and unequally loaded by phases, a three-phase model of SSSC is presented. Models are verified on a test case.

1. INTRODUCTION

Due to the growing of number of small renewables connected to the distribution system, to ensure the appropriate voltage conditions at time when some renewables do not produce any power, it is necessary to use an active solution. One of the possible solutions is to include a static synchronous series compensator (SSSC) in the system. Its advantage is that the voltage and power control is independent of the current flowing through the SSSC. This means that SSSC synchronises settings depending on the needs of the system or to achieve specific controlled variable. However, before adding a new device in the power system, calculations are made for different operating conditions. This includes also power-flow analysis, for which a suitable model is needed. Therefore, in this article a new model of SSSC suitable for use in radial network with forward-sweep algorithm is presented.

2. FORWARD-SWEEP ALGORITHM

Forward-sweep algorithm is most commonly used method for calculation of power-flows in radial distribution networks. It is suitable to use in systems with the high R/X ratio, in which Newton-Raphson method does not converge [2].

The method is based on a calculation of the injected currents and the voltage drop caused by the injected currents [3]. It is very important to know whether loads have constant power (n = 0), constant current (n = 1) or constant impedance character (n = 2). In a three-phase system for current injection calculation it is also very important to know whether loads are star (1) or delta (2) connected. Next step is calculation of current injections of shunt capacitances (3). The last two steps in calculating power-flow applying forward sweep algorithm are calculation of line currents (4) and node voltages(5).

$$\left[\underline{Il}_q^p\right] = \left[\left(\frac{\underline{Sl}_q^p}{\underline{U}_q^p}\right)^* \cdot \left|\underline{U}_q^p\right|^n\right] \tag{1}$$

$$\left[\underline{Il}_q^p\right] = \left[\left(\frac{\underline{Sl}_q^{pp}}{\underline{U}_q^{pp}}\right)^* \cdot \left|\underline{U}_q^{pp}\right|^n - \left(\frac{\underline{Sl}_q^{pp}}{\underline{U}_q^{pp}}\right)^* \cdot \left|\underline{U}_q^{pp}\right|^n\right] \tag{2}$$

$$\left[\underline{Ish}_q^p\right] = \frac{1}{2}\left[\underline{Y}_{sh}\right]\left[\underline{U}_q^p\right] \tag{3}$$

$$\left[\underline{I}_{rq}^p\right] = \sum_{i=1}^{N(rq)}\left[\underline{Il}_q^p\right] + \sum_{i=1}^{N(rq)}\left[\underline{Ish}_q^p\right] \tag{4}$$

$$\left[\underline{U}_q^p\right] = \left[\underline{U}_r^p\right] - \left[\underline{Z}_{rq}\right] \cdot \left[I_{rq}^p\right] \tag{5}$$

where is: $\underline{Il}_q^p$ - Current injected by load in node *q*,

$\underline{Sl}_q^p$ - phase load at node *q*,

$\underline{Sl}_q^{pp}$ - load between two phases at node *q*,

$\underline{U}_q^p$ - phase voltage at node *q*,

$\underline{U}_q^{pp}$ - voltage between two phases at node *q*,

$\underline{Ish}_q^p$ - phase shunt current at node *q*,

$\underline{Y}_{sh}$ - shunt admittance,

$\underline{I}_{rq}^p$ - current between nodes *r* and *q*,

$\underline{U}_r^p$ - phase voltage at node *r*,

$\underline{Z}_{rq}$ - line impedance.

The procedure containing steps from (1) to (5), repeats until the maximum voltage or current difference between two steps is small enough.

3. STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC)

SSSC is a member of FACTS (flexible alternating current transmission system) family, which may be applied for nodal voltage or power-flow control. It consists of transformer and AC/DC converter with battery or capacitor [1].

In this paper the models of SSSC with capacitor are described. This SSSC injects the voltage into the power system, which is perpendicular to the current, disregarding the device losses. The SSSC is actually acting as a virtual capacitive or inductive element, depending on the sign of the injected voltage. At this point it should be mentioned that the there are several options, how the SSSC is connected to the system. This fact must be taken into account, when a three-phase models of SSSC are modelled due to its impact on system. Another fact is that in radial power systems the possibilities are limited to injected voltage and nodal voltage control.

The models of SSSC that are suitable to use with forward-sweep algorithm are based on current model of SSSC for Newton-Raphson method. Fig. 1 shows the current model, which has one additional node S, introduced for calculation purposes and does not represent the actual node. This node enables to separate the losses from the regulation [4].

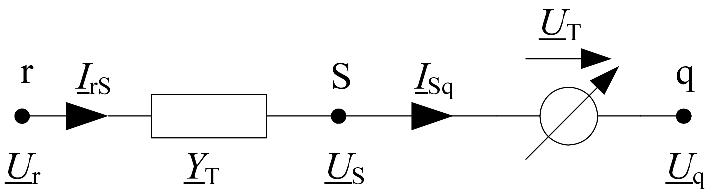

Fig. 1: Current model of SSSC.

4. THREE-PHASE MODEL OF SSSC

The three-phase model of SSSC for forward sweep algorithm requires data regarding the SSSC connection. First option is connection via three single-phase transformers to one AC/DC converter and the second option is connection via three-phase delta/wye transformer to one converter. In both cases the injected voltage is perpendicular to phase current in each of the phases and the current flowing through SSSC remains constant (6). Also the losses (7) of SSSC are calculated the same for both types of connection.

Additionally, in second case, the delta/wye connection of transformer must be taken into account, which reflects as the sum of injected voltage for all three phases is zero.

$$\left[\underline{I}_{rS}^{p}\right]=\left[\underline{I}_{Sq}^{p}\right] \tag{6}$$

$$\left[\underline{U}_{S}^{p}\right]=\left[\underline{U}_{r}^{p}\right]-\left[\underline{Z}_{T}\right]\cdot\left[\underline{I}_{rS}^{p}\right] \tag{7}$$

kjer je: $\underline{I}_{Sq}^{p}$ - Current between nodes S and q,

$\underline{I}_{rS}^{p}$ - current between nodes r and S,

$\underline{U}_{S}^{p}$ - phase voltage at node S,

$\underline{U}_{r}^{p}$ - phase voltage at node r,

$\underline{Z}_{T}$ - impedance of the SSSC.

4.1 Injected voltage control

4.1.1 Three single-phase transformers

For injected voltage control by SSSC with three separate single-phase transformers the control strategy is based on required injected voltage magnitude and known current phase angle (8). The current through SSSC remains constant (6) and the losses are represented with impedance (7). The amplitude of injected voltage can be different or the same for all three phases. The equations for mono-phase presentation of SSSC are the same, referred to only one phase.

$$\left[\underline{U}_q^p\right] = \left[\underline{U}_S^p\right] + \left[U_T^p \cdot \mathrm{e}^{\left(j\cdot\left(\delta_{\underline{I}_{Sq}}^p + \frac{\pi}{2}\right)\right)}\right] \tag{8}$$

kjer je: $\underline{U}_q^p$ - phase voltage at node q,

$\underline{U}_S^p$ - phase voltage at node S,

U_T^p - phase injected voltage SSSC,

$\delta_{\underline{I}_{Sq}}^p$ - angle of current between nodes S and q.

4.1.2 Three-phase transformer

By applying the SSSC with delta/wye connected transformer only injected voltage at one phase can be controlled. The injected voltages in other two phases are calculated by law of sine (9) and (10). Also in this case (6) and (7) are still valid. Calculated nodal voltage depends on injected voltage and known current phase angle (11).

$$\begin{aligned}
\delta_T^a &= \left|\pi - \left|\delta_{\underline{I}_{Sq}}^c - \delta_{\underline{I}_{Sq}}^b\right|\right| \\
\delta_T^b &= \left|\pi - \left|\delta_{\underline{I}_{Sq}}^a - \delta_{\underline{I}_{Sq}}^c\right|\right| \\
\delta_T^c &= \left|\pi - \left|\delta_{\underline{I}_{Sq}}^b - \delta_{\underline{I}_{Sq}}^a\right|\right|
\end{aligned} \tag{9}$$

$$\frac{U_T^a}{\sin\delta_T^a} = \frac{U_T^b}{\sin\delta_T^b} = \frac{U_T^c}{\sin\delta_T^c} \tag{10}$$

$$\left[\underline{U}_q^p\right] = \left[\underline{U}_S^p\right] + \left[U_T^p \cdot \mathrm{e}^{\left(j\cdot\left(\delta_{\underline{I}_{Sq}}^p + \frac{\pi}{2}\right)\right)}\right] \tag{11}$$

kjer je: δ_T^p - Phase angle for calculating the law of sines,

$\delta^p_{\underline{I}_{Sq}}$ - angle of current between nodes S and q,

U^p_T - phase injected voltage of SSSC,

$\underline{U}^p_q$ - phase voltage at node q,

$\underline{U}^p_S$ - phase voltage at node S.

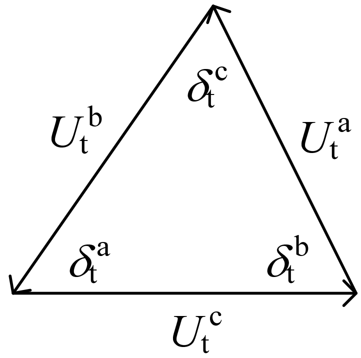

Fig. 2: Law of sines and injected voltage.

4.2 Nodal voltage control

4.2.1 Three single-phase transformers

Model of SSSC with three single-phase transformers is more useful and quite simple. The current remains the same (6) and the losses are calculated by (7). Nodal voltage control is described by (12). The equations for mono-phase presentation of SSSC are the same, referred to only one phase.

At this point authors would outline that nodal voltage control for each phase is independent and that there are two possible solutions for nodal voltage control for each phase as is shown on Fig. 3. The best solution of nodal voltage for each phase is the one, which gives smaller virtual impedance (13).

$$\underline{U}^p_q = U^p_{def} \cdot \mathrm{e}^{\left(j \cdot \left(\delta^p_{\underline{I}_{Sq}} \pm \arccos\left(\frac{U^p_S}{U^p_{def}} \cdot \cos\left(\delta^p_{\underline{U}_S} - \delta^p_{\underline{I}_{Sq}}\right)\right)\right)\right)} \tag{12}$$

$$Z^p_{SSSC} = \left| \frac{\underline{U}^p_q - \underline{U}^p_S}{\underline{I}^p_{Sq}} \right| \tag{13}$$

kjer je: $\underline{U}^p_q$ - Phase voltage at node q,

U^p_{def} - required phase voltage amplitude,

$\delta^p_{\underline{I}_{Sq}}$ - angle of current between nodes S and q,

$\underline{U}_S^p$ - phase voltage at node *S*,

$\delta_{\underline{U}_S}^p$ - phase angle of voltage at node *S*,

Z_{SSSC} - imaginary impedance of the SSSC,

$\underline{I}_{Sq}^p$ - current between nodes *S* and *q*.

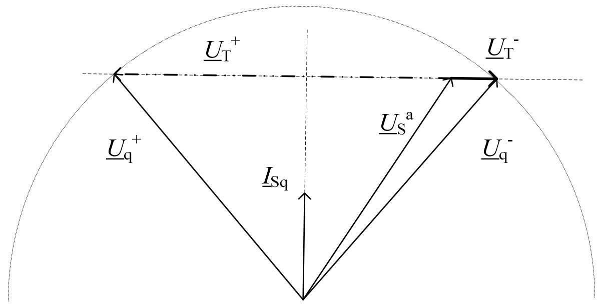

Fig. 3: Two solutions of nodal voltage regulation at node *q*.

4.2.2 Three-phase transformer

In this case only nodal voltage of one phase can be defined, the nodal voltages of other two phases are determined with law of sines and injected voltage, as in case of injected voltage control, where SSSC consist of delta/wye connected transformers. Also in this case (6) and (7) are still valid. Next the nodal voltage for one phase (12) and virtual impedance (13) in order to achieve convergence and avoid multiple solutions problem is calculated. Then injected voltage at controlled phase is defined (14). The injected voltages of other two phases are defined by law of sines (9) and (10). The nodal voltage of other two phases is calculated from injected voltage (11).

$$\underline{U}_T^p = \underline{U}_q^p - \underline{U}_S^p \tag{14}$$

where is:

$\underline{U}_T^p$ - phase injected voltage of SSSC,

$\underline{U}_q^p$ - phase voltage at node *q*,

$\underline{U}_S^p$ - phase voltage at node *S*,

5. RESULTS

All described models of SSSC have been tested on the IEEE 34 bus test feeder. Two SSSCs are placed in the system. First one is include between node 814 and node 850, and the second one is placed between node 852 and node 832. At each test case both SSSCs are the same, with impedance of SSSC $\underline{Z}_T$ 2.07 Ω. The required maximum mismatch is 10^{-8} p.u..

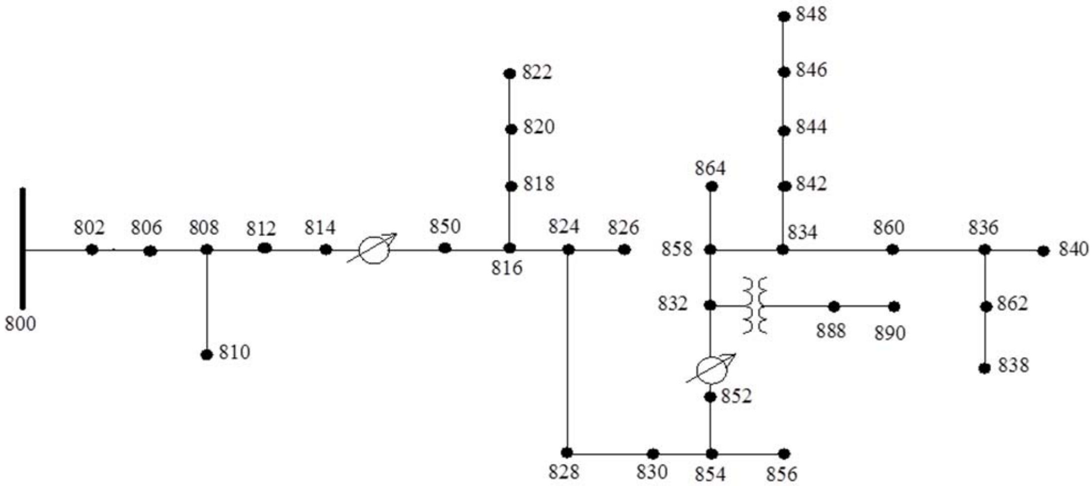

Fig. 4: IEEE 34 bus test system.

At first, SSSC models for injected voltage regulation were tested. Fig. 5 shows the number of iterations to reach desired injected voltage. The number of iterations is almost the same if the SSSC is not included in the system or if SSSCs are included and injected voltage is between -0.1 p.u. and 0.2 p.u.. If the controlled injected voltage is outside this range, the number of iterations is higher, but not significantly. Controlled injected voltage is in all three phases the same if the SSSCs are connected through three separate single-phase transformers. In second case, where SSSCs are connected through delta/wye connected transformer, the injected voltages of phase b and c are equal or lower than as in regulated phase a. The reason is in system load configuration.

Fig. 6 presents number iterations which are needed to achieve controlled nodal voltage. As is it seen, the number of iterations is much higher for higher controlled nodal voltage. In the most extreme cases even two to three times higher. The reason for that is that nodal voltage depends on various different causes. If the SSSCs are connected through three separate single-phase transformers, the controlled nodal voltage is the same in all phases. In case that SSSCs are connected through delta/wye connected transformer, the nodal voltage is higher in phase b and c then in regulated phase a.

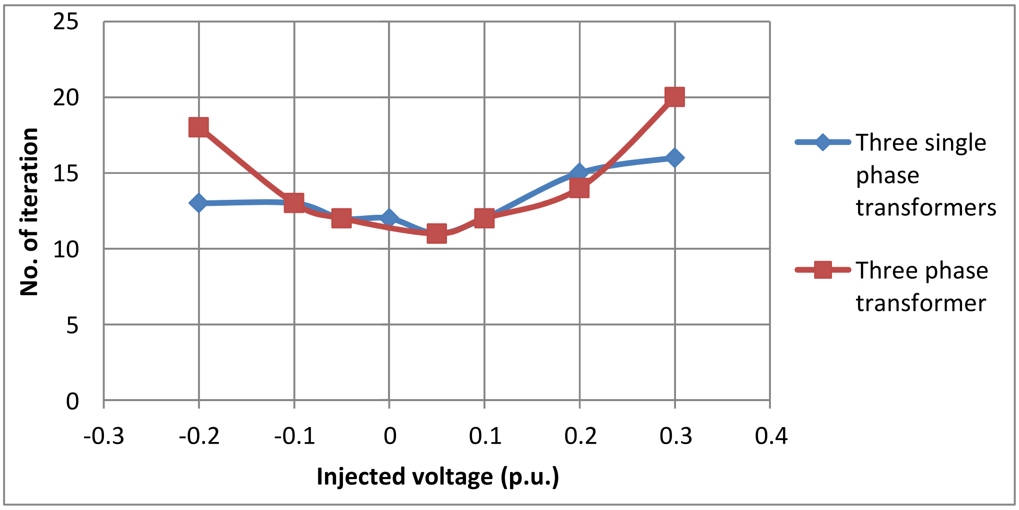

Fig. 5: Number of iteration for injected voltage regulation.

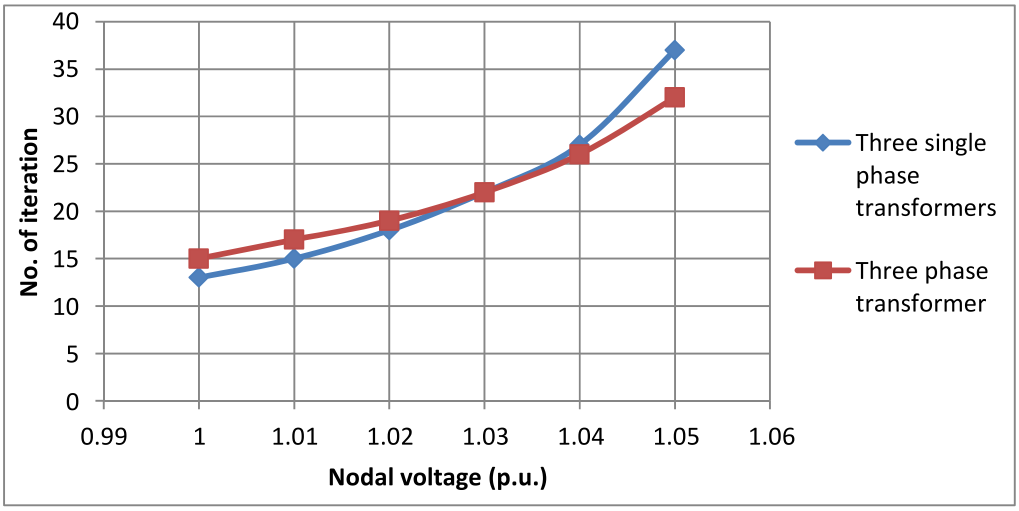

Fig. 6: Number of iteration for nodal voltage regulation.

6. CONCLUSION

Newton-Raphson method does not converge in radial networks. Therefore, the forward sweep algorithm may be used, for which models of SSSC have been developed for mono-phase as well as for three-phase analysis. By developing three-phase model of SSSC, the connection of SSSC to the system must be also taken into account. SSSC can be connected via three single-phase transformers or through one three-phase transformer with a delta/star connection. All three-phase models were tested on the test network. In all cases, the model converges. At this point we would like to add that it would be reasonable to improve the model of SSSC for nodal voltage regulation in order to reduce the number of iterations required to achieve the desired mismatch.

7. REFERENCES

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