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A New Structure for "Sen" Transformer Using Three Winding Linear Transformer

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ABSTRACT

In this paper a new structure for "Sen" transformer (ST) is introduced, by using three winding transformers with neutral point in order to use negative value of compensating voltage. Combination of taps will be adjusted by a novel algorithm, to control the required active and reactive powers, separately. This paper tries to focus on three parts. First of all there is an introduction on the concept of ST structure what comes next is a try to work on power flow control by using PI controllers and an algorithm to find the best and efficient combination of taps, finally proposed idea and algorithm will be implement on a practical system. Implementation of the system consists of two separated and related parts. The first one is about transmission line and Sen Transformer and theinteraction between them. The second part is programing codes that adjust taps for required active and reactive powers.

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1. INTRODUCTION

In the last decades lots of researches and developments have been conducted on theflexible AC transmission systems (FACTS) as effective equipment to regulate voltage and power flow in transmission lines [1]-[2]. Despite their advantages, in practical systems there are too many transformers that they can be used asan inexpensive FACTS tools, If we just change structure of the transformers of transmission lines in a way that will be possible to utilizethem as a FACTS devices it will be technically and Economically efficient In practical ranges.This is the seminal advantage of Sen Transformer.Analyses on performances of phase shifting transformer and tapchanger transformer could be useful to comprehend how ST works [3]-[7]. Kalyan K. Sen and Mey Ling Sen introduce ST and discussed about it and compare ST with UPFC in [8] and [9]. There are a lots of researchs about UPFC and USSC control methods and performances that could be useful in Sen Transformer controller desing [10]-[14]. In [15]-[16], authors discussed the structure of windings and an algorithm to find the combination of taps. Some article has discussed about combination of high-capacity ST and a small capacity UPFC has investigated their performance [17]. There are authors that have investigated performance of ST and UPFC economically and have compared them with each other [18]-[19]. A study has done to evolve the Controller for Static Synchronous SeriesCompensator Based on Control Strategy of Sen Transformer [20].This paper presents a novel Structure for secondary windings and an algorithm to choose taps in order to achieve larger area of compensation. Figure 1 illustrates Sen Transformer position in transmission line.

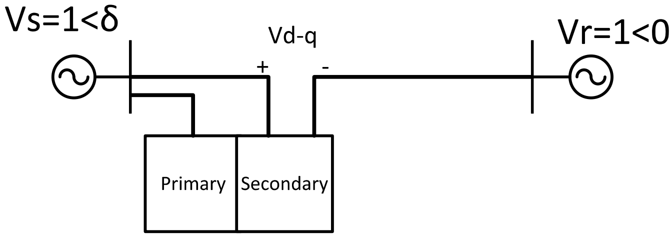

Figure 1. Location of Sen Transformer in transmission line

It will be installed right after sending end bus. By adding voltage with certain amplitude and phase angle we will have a new sending effective voltage called (V_{se}) with new Phase angle δ_e, as shown in Figure 2. It can be proved that active and reactive powers could be calculated from (1) and (2).

$$P_r = \frac{V_{se}V_r}{X_l} Sin\delta_e \quad (1)$$

$$Q_r = \frac{V_{se}V_r}{X_l} (Cos\delta_e - 1) \quad (2)$$

Where V_{se} and V_r are amplitudes of sending and receiving sides voltages and δ_e is the effective angle between voltages of both sides. We use effective value of all parameters to apply the effects of compensator. All of these parameters have effect on the active and reactive powers in transmission line so that is why we use them to control compensator, implement a control strategy for power flow and an algorithm to calculate the taps. In tap changers we can only give specified value to taps, in other words, taps change discontinuously and step by step. It can be one of the disadvantages of Sen Transformer compare to UPFC, which can change parameters of compensator continually. Because of this Property of Sen transformer we can't achieve all range of compensating and we must design a method which is able to take the compensator to the nearest state of compensating that transformer can achieve. This paper is comprised of three sections. First of all we introduce Sen Transformer and conventional structure of its windings and a new structure which covers bigger area of compensating and then in the second part we implement a control strategy and algorithm based on matlab codes to control value of taps. At the end, we show the results of simulation and mathematical equations.

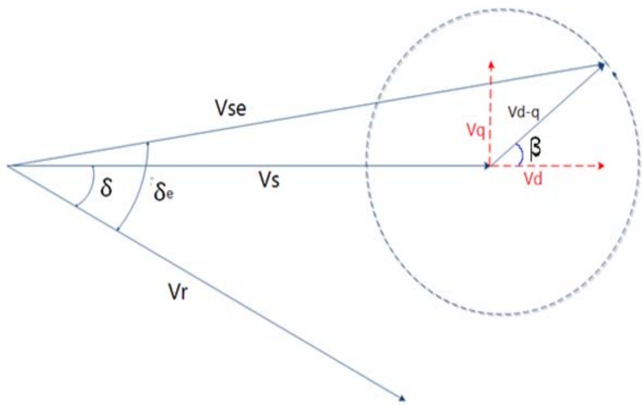

Figure 2. Phase diagram

2. STRUCTURE OF SEN TRANSFORMER

In conventional Sen Transformer as depicted in Figure 3, for compensating each phase, we use the summation of three voltages of three linear transformers that are series together. These three voltages have positive value and for deferent β, deferent combination of transformers will participate in compensating each phase. For example, in phase A for (0<β<120) ratio (Kaa and Kac) of phases A and C will participate in compensating. For (120<β<240) ratio (Kac and Kab) of phase C and B will participate in compensating. And finally for (240<β<360) ratio (Kab and Kaa) of phases B and A will participate in compensating. For other phases, B and C also the performance of taps will be the same The only difference lies in the value of B which will be (β+120) for phase C and (β+240) for phase B. the ratio of compensating for phase C will be determinate by (Kca, Kcb, Kcc) and for phase B will be determinate by (Kba, Kbb, Kbc). It must be noted that (Kaa, Kbb, Kcc) and (Kab, Kbc, Kca) and (Kac, Kba, Kcb) are equals in order to have symmetrical compensating.

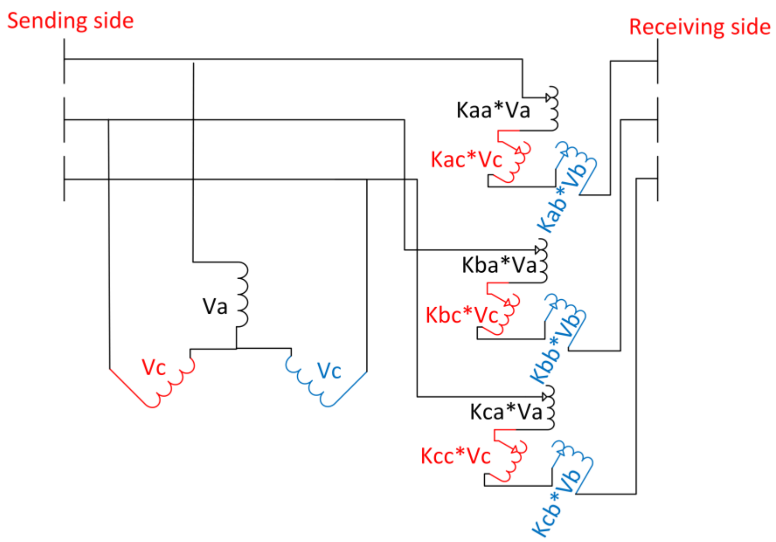

Figure 3. Schematic diagram of conventional ST

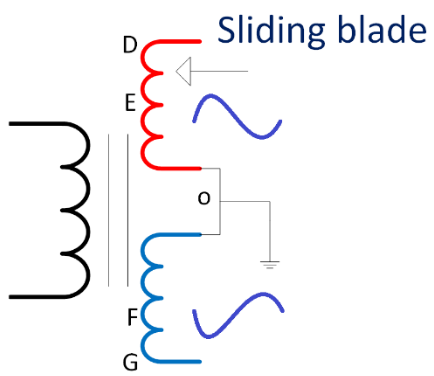

Figure 4. Three winding linear transformer

In this paper we suggest a new structure, as will be seen at the next page, which is capable of covering bigger areas of compensating. Figure 4 shows three windings transformer with neutral point in middle of secondary. The secondary has made up from two positive and negative parts. By sliding the blade from D to E in positive area, the value of voltage decreases but still remains positive until it became zero in O. pushing the sliding blade in negative area, value of voltage increases but negative, F point. And finally at G point we can achieve maximum negative value of voltage. The performance of propose structure is similar to conventional ST and for each phase we use summation of three symmetrical voltages in order to compensate. But there is one fundamental difference, in conventional ST compensating voltages only could be positive, but in this case they can be negative and because of this ability ST can achieve more reliability in order to regulate power flow.

Data of system studied with ST Such as resistance and impedance of transmission line and windings can be found from Table 1. Figure 5 shows general structure of transmission line and ST windings connected together and how the collection stays together.

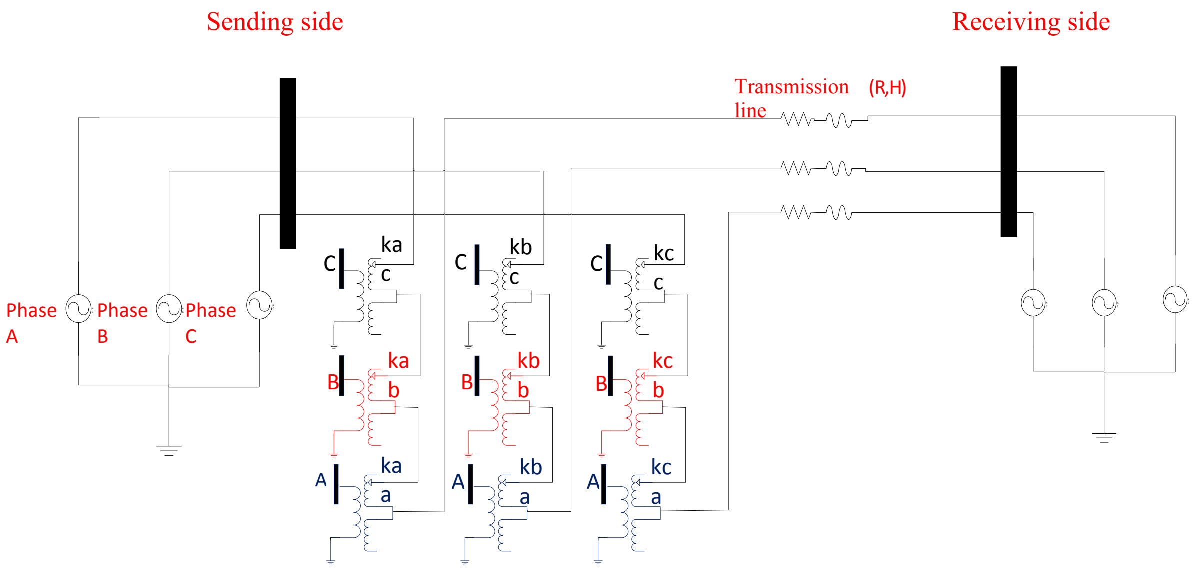

Figure 5. General structure of transmission line and ST windings

The value of windings ratio (Kaa, Kbb, Kcc, Kab, Kbc, Kca, Kac, Kba, Kcb) can be positive and negative.At any moment, summation of two voltages of three winding, according to value of β, participate in compensating. For example, to compensate phase A for (0<β<60) ratio (Kaa and Kab) of phases A and B will participate in compensating. But it should be noted that the ratio of phase B that participate in compensating is negative. For (60<β<120) ratio (Kac and Kab) of phases B and C will participate in compensating where Kab is negative. By the same way, for (120<β<180) ratio (Kac and Kaa) of phases A and C will participate in compensating where Kaa adjust on negative side. For (180<β<240) ratio (Kaa and Kab) of phases A and B will participate in compensating where Kaa is negative. Remember (Kaa, Kbb, Kcc) and (Kab, Kbc, Kca) and (Kac, Kba, Kcb) are equals in order to have symmetrical compensating, and all of them can be positive, negative and zero according to value of β.

Table 1. Data of Electrical System and ST

Parameters	*Value*
Nominal values of power and voltage	160 MVA and 168 kV
Sending end voltage	1< 20 pu
Receiving end voltage	1< 0 pu
Transmission line impedance and inductance	4.5159 Ω and 0.20919 H
Primary, secondary and Tertiary windings impedances & inductances	R= 0.002 pu and L= 0.08 pu
Rating of ST transformer	30 MVA

3. CONTROL STRATEGY
3.1. Splitting Compensating Voltage into Pharos Component

Considering ST transformer as what was shown in Figure 5, for adjusting taps positions we must have an algorithm in order to select the best position in all ranges of compensating. The taps change in steps of 0.1pu from zero to 0.4 pu discontinuously. But In order to have simplified simulation, we consider that it change without any delay. Figure 6 demonstrates six zones and in all of them compensating voltage vector can only stay on the crossing points that was made up by dashes line. Let V_{d-q} be the required compensating voltage which falls in area between 4 satisfactory points. In UPFC there were no problems for this voltage but, in ST because of discontinuous nature of compensating voltage must be adjust on the nearest Point. For this purpose we can calculate the value of error ε_K (distance between compensating vector and acceptable point) and choose the point dedicated by minimum value of ε_K(k=1, 2, 3 or 4).

Apparently, it can be difficult and Time-consuming to calculate ε_K for each point. In this paper to find nearest point to vector V_{d-q} , we use an algorithm that it can be easily implement with fortran , matlab , c++ …codes to interface with the rest of system.

For example by attention to Figure 6 First of all we calculate value of V_d and keep in mind that according to the zone that we are in, V_d and V_q can be placed in the same direction with phasors a, b, c and negative value of these three phasors.

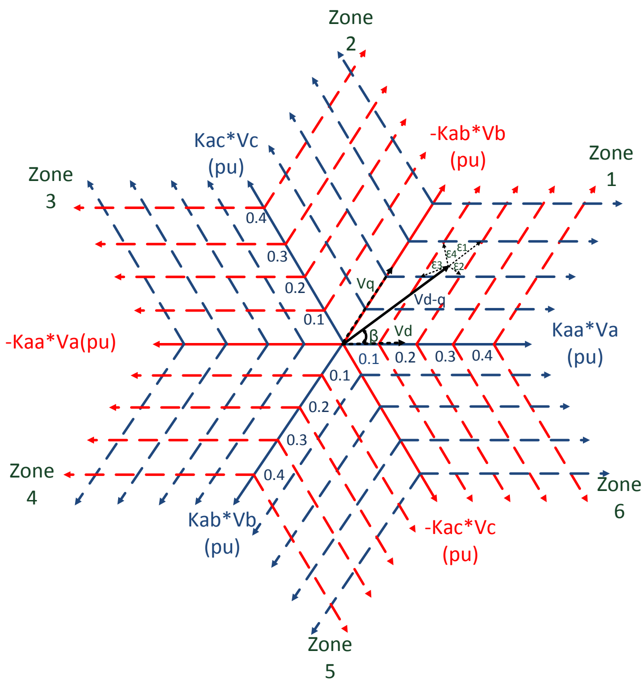

Figure 6. Tap position grid for the construction of Vd-q

Here is an example we try to explain the algorithm, Imagine that the compensating vector is in zone 1 and value of $V_d$andV_q have determined 0.24 pu and 0.36 pu respectively. Now if we use following codes in matlab command windows, the result will be nearest point to the compensating vector and it is the most convincing point.

$$K_{aa} = \frac{floor[(10 * 0.24) + 0.5]}{10} = 0.2$$

$$-K_{ab} = \frac{floor[(10 * 0.36) + 0.5]}{10} = 0.4$$

Where word "floor" represents the ceiling function in Matlab. This algorithm for V_d and V_q between (0 to 0.05) , (0.1 to 0.15), (0.2 to 0.25) and (0.3 to 0.35) gives as tap positions at 0, 0.1, 0.2, 0.3 and for V_d and V_q between (0.05 to 0.1) , (0.15 to 0.2) , (0.25 to 0.3) and (0.35 to 0.4) give as tap positions at 0.1, 0.2, 0.3 and 0.4 . It is obvious that by implementation this algorithm, the nearest point to the compensator vector will be find and there is no needs to calculate error ε_K.

Figure 7 shows all steps of adjusting taps position as flow chart in order to adjust taps position in the efficient places. At first, it gets phase angle of voltage vector and its amplitude as inputs we adjust taps for phase a, and then repeat these steps for other.

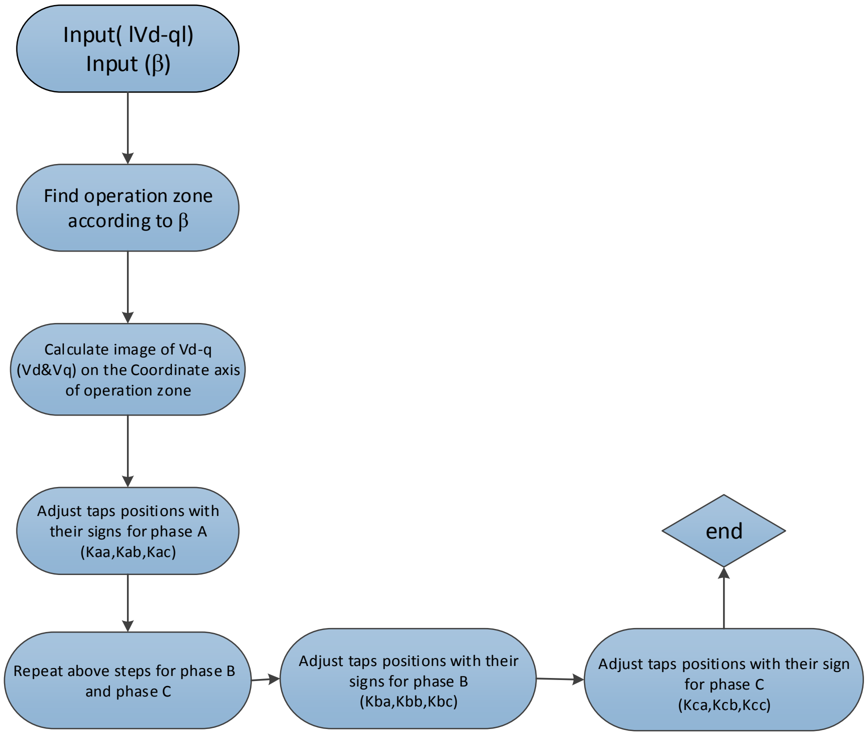

Figure 7. Flow chart for matlab codes to determine taps position

3.2. Active and Reactive Power Control Techniques

According to Figure 2 it is obvious that by changing in V_q, value of δ changes and V_q have most influence on δ. Equation (1) shows that receiving end, active power is proportional with δ, so we can control active power by V_q indirectly.

With attention to figure 2 it can be also extract that the effective amplitude,V_{se} impressible fromV_d. Equation (2) shows that reactive power in receiving side is proportional with V_{se}. Thus it is possible to control receiving end reactive power by V_d indirectly.

Above concepts are used as techniques to control active and reactive power in transmission line separately. As we can see in Figure 8, by receiving side voltage and current, value of active and reactive power will be measured and they will be compared with reference value of these powers. Result will be used as inputs for PI controllers.

Outputs of these controllers dedicate amplitude and phase angel of compensator. Voltage can be determined and be used as input for matlab interface, In order to adjust taps position. The principle of the algorithm of tap selecting was discussed in last chapter, as a result the outputs of power control diagram performs as an input for matlab interface taps selector. By choosing windings that participate in compensating for each phase, power flow in transmission line can be controlled as was discussed.

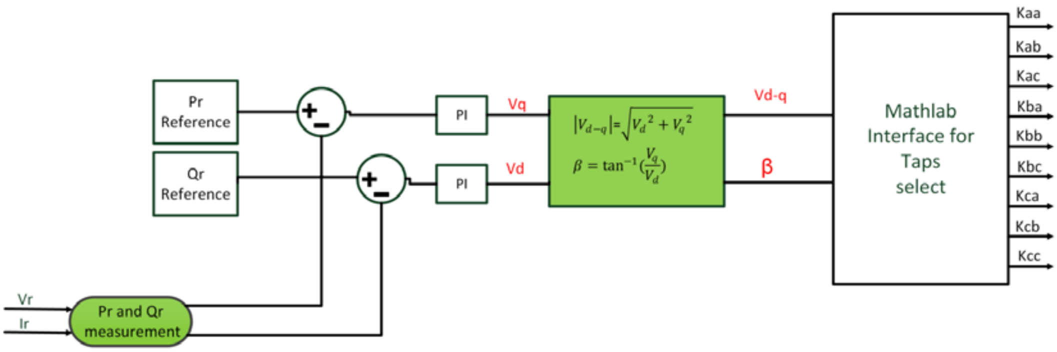

Figure 8. Power flow controls block diagram

4. POWER EQUATIONS AND SIMULATION RESULTS

4.1. Power Equations

In power systems, active and reactive power assimilated by receiving end bus will be calculated from (1) and (2). According to these equations we have:

$$P_r{}^2 + (Q_r + \frac{V^2}{X})^2 = \left(\frac{V^2}{X}\right)^2 (Sin^2\delta + Cos^2\delta)$$

$$P_r{}^2 + \left(Q_r + \frac{V^2}{X}\right)^2 = \left(\frac{V^2}{X}\right)^2 \quad (3)$$

$$IF\ :\ (Sin^2\delta + Cos^2\delta) = 1\ \ \& \frac{V^2}{X} = 1\,pu$$

$$P_r{}^2 + (Q_r + 1)^2 = 1 \quad (4)$$

Equation (4) denote that changes in active and reactive power against each other will be on a circle in the P-Q coordinate plane with (0,-1) as center of circle and 1 (pu) as radius.

Now by using ST or UPFC (both of them are similar but ST has less speed and accuracy) as a compensator in sending end and according to [1] , there will be some changes in powers, proportional with amplitude and phase angle of compensating as it is calculate below.

$$\mathrm{I} = \frac{P - jQ}{V} = \frac{V_s + V_{d-q} - V_r}{jX}$$

$$P_r = \frac{V^2}{X} Sin\delta + \frac{V_{d-q}V}{X} Sin(\delta + \beta) \quad (5)$$

$$Q_r = \frac{V^2}{X}(Cos\delta - 1) + \frac{V_{d-q}V}{X} Cos(\delta + \beta) \quad (6)$$

$$IF\ :\ (Sin^2\delta + Cos^2\delta) = 1\ \ \& \frac{V^2}{X} = 1\,pu$$

$$P_r = P_{r_0} + V_{d-q}(pu)\ Sin(\delta + \beta) \quad (7)$$

$$Q_r = Q_{r_0} + V_{d-q}(pu)\ Cos(\delta + \beta) \quad (8)$$

$$(P_r - P_{r_0})^2 + (Q_r - Q_{r_0})^2 = (V_{d-q}\,(pu))^2 \quad (9)$$

Equation (9) tells as, in the presence of UPFC (or ST similarly) active and reactive power changes against each other will be on a circle with (P_{r_0}, Q_{r_0}) as center of the circle and $V_{P-q}(pu)$ as radius. $P_{r_0} and Q_{r_0}$ dedicate to value of active and reactive power in the absence of compensator.

Figure 9 illustrates the relationship between active and reactive powers according to above equations (3 to 9). As it can be seen, ST cannot perform completely similar to UPFC and there is errors between UPFC and ST accept on some Particular angels for β.

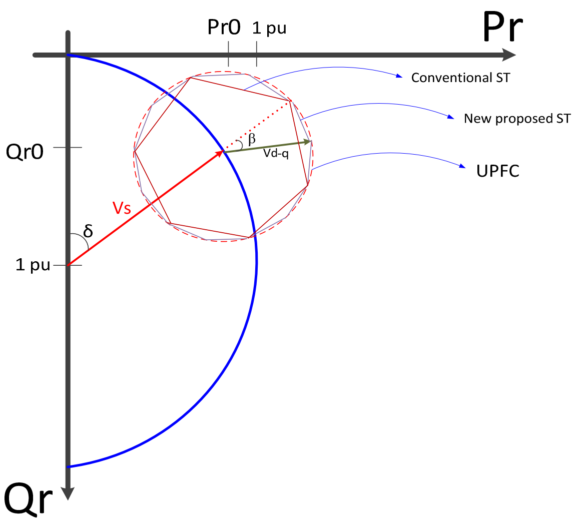

Figure 9. Relationship between Pr and Qr In the presence of UPFC, conventional ST and new expressed ST

In conventional ST for β equal to 0, 60, 120, 180, 240, 300 and 360 degree performance is exactly same with UPFC but for other angels error is equal to deference between circle and octagonal (vacuum corners). It is obvious that new proposed ST could perform faster and more accurate and vacuum corner will be mostly eliminated. In this case, performance of ST approximately slide on UPFC and is exactly same for angels 0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330 and 360 degree.

4.2. Simulation Results

In order to investigate the proper performance of proposed ST and techniques, system illustrated in Figure 5 is implemented in Simulink of matlab 2014 and to specify position of taps, the codes are written in a block named sfunction that provide situation to interface codes with Simulink. And result illustrated in Figure 10 to Figure 12. Figure 10, shows changes in active and reactive power. V_{se} could be seen in Figure 11, current received by receiving end is shown in Figure 12.

Primarily, system was conducted without any compensating until time equal 5 s, then V_{d-q}= 0.1< 30 applied to the system. The value of active and reactive power will be sustained at 145.54 MW and 97.07 MVAR respectively, sending end voltage reaches to 1.2 of its nominal value and current reaches to 0.25 pu.

In time equal 10 s, compensating vector changes to another value, V_{d-q}= 0.1< 270 and active and reactive power changes again and stops at 58.98 MW and 30.67 MVAR. Voltage and current reachs to 1.1 and 0.1 (pu). In time 15 s and 20 s compensating vector change to 0.4< 270 and 0.4<150, the results of this changes are shown in Figure 10 to Figure 12.

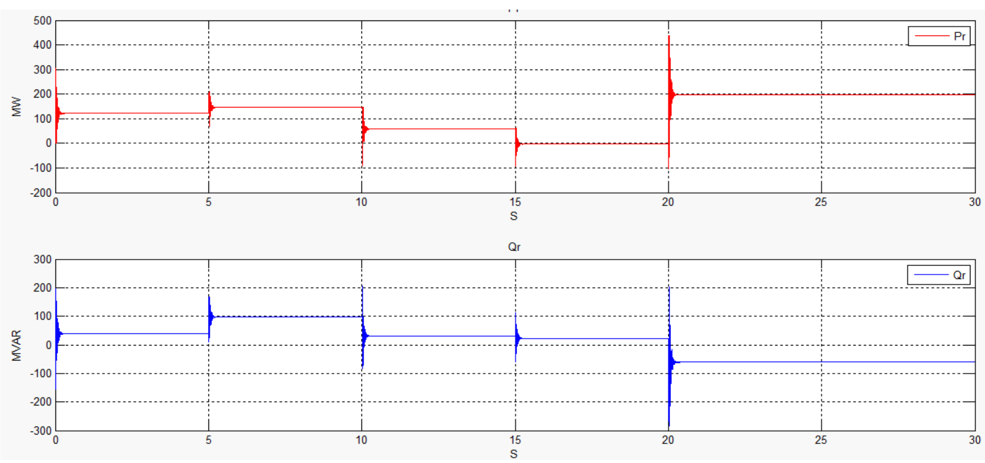

Figure 10. Simulink results for values of active and reactive power

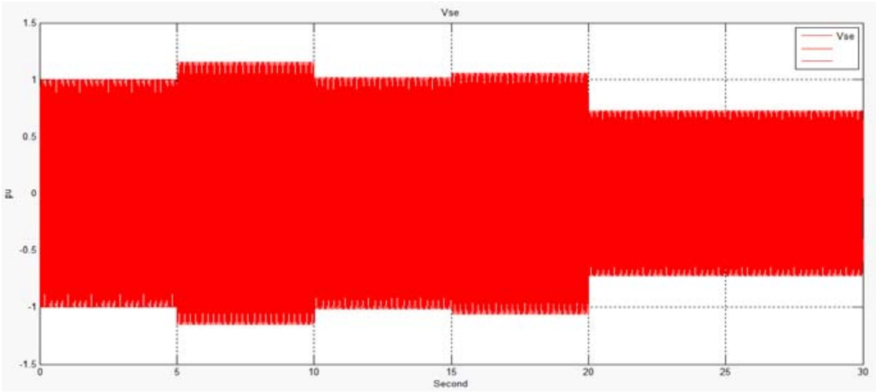

Figure 11. Changes in value of sending end voltage (Vse)

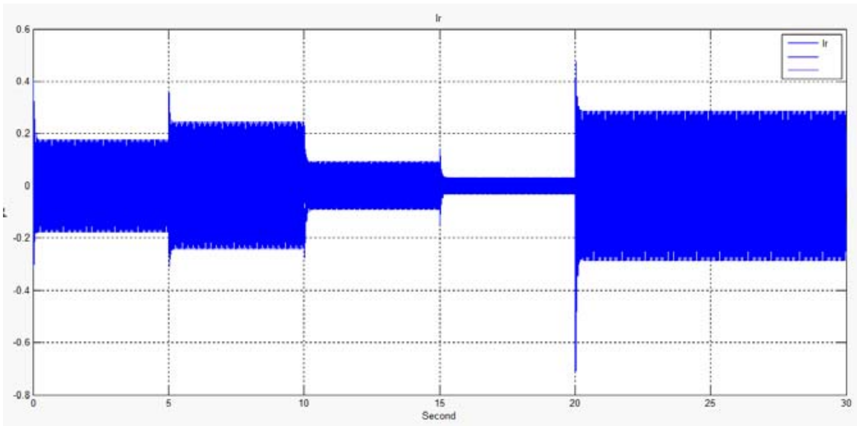

Figure 12. Changes in value of current (Ir)

5. CONCLUSION

According to this paper it can be realized that although using UPFC in power system as FACTS equipment to regulate voltage and power flow gives as more flexibility and better reaction against changes in Demands, ST is very expensive and it is More To put it eloquently, transformers in grid can perform similar to UPFC. Although regulate voltage and power flow is slower and more discontinuous, it takes acceptable rate. In this paper we proposed a new structure and algorithm for ST that gives as better speed and flexibility, and it has been proved that proposed structure can be more similar to UPFC.

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