The Numerical Estimation Method of Series FACTS Compensator Based on Injection Model of Voltage Source Inverter

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Abstract— **This paper presents new numerical injection model of Inter Line Power Flow Controller (IPFC). Indeed, linear model of voltage source inverter of IPFC is improved to estimate steady-state operation of IPFC as well as Static Synchronous Series compensator (SSSC) in power system. The proposed method estimates the effect of IPFC on active and reactive line power flow with SSSC for three modes such as resistive, capacitive and inductive. Thus, it is recommended that the proposed technique can be applied for prediction of initial injected voltage and its phase angle of IPFC and SSSC for their modeling in real system. The tested system for simulation is based on IEEE two machine systems. The result of simulation and the numerical analysis shows the robust accuracy of obtained estimation of IPFC and SSSC.**

Keywords-component; Numerical estimation, active and reactive power, Static Synchronous Series Compensator, Inter Line Power Flow Controller, voltage source inverter.

I. INTRODUCTION

A series capacitor is used for increasing active power flow at receiving end line in power grid. But, difficulties of series capacitors usage are emerged in [1-2]:

1- Increasing the stray reactive power.
2- Sub-synchronous resonance phenomenon.
3- Operation of series capacitors based on thyristor switch.

Static Synchronous Series Compensator (SSSC) can be used for solving the mentioned problems. For instance, system isn't challenged to resonance phenomenon [3], because the SSSC can inject the reactive power into the system in fundamental system frequency. However, most defect of series capacitors are obviated by SSSC. But, inability of SSSC is appeared when it is needed to control independently of active and reactive power flow at receiving end line. To decrease line reactive power in some conditions, SSSC has not enough capacity to absorb stray reactive power of power system. Because, injecting capacity of voltage source inverter (VSI) is not considered for SSSC [3, 5]. To overcome SSSC incompetence, two devices were proposed, The Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC) [4]. But, it is known that capacity of IPFC in injecting active power to line is more noticeable than UPFC [7]. Therefore, role of IPFC for controlling of active and reactive power and voltage in power system is well known [15]. One of these roles is in state estimation of power system with FACTS devices for online monitoring [16-17].

In this paper, concept of state estimation for IPFC developed and improved based on proposed injection model. First of all, the proposed injection model of IPFC is introduced and used for improving capacity of VSI in IPFC for compensation of active and reactive power in power system. Indeed, this method uses other lines for balancing of power system active and reactive power. Furthermore, main contribution of proposed method for online estimation of IPFC is in utilizing of linear model of IPFC based on injection model. Three modes of IPFC are considered such as resistive, capacitive and inductive and compared with SSSC. In resistive mode of IPFC, reactive power flow is purposed to decrease to 0 P.U and increasing real power flow at receiving end line to 1 P.U. Also, in capacitive mode of this model, maximum injecting of active power occurs to satisfy the active power demand at receiving end line. In inductive mode, line reactive and active power flows are decreased [6, 8, 12-13]. So, novel method that has been introduced in this paper is linear equations which are acquired by three modes of IPFC. These equations estimate with high conjecture that can compare with value of active power and reactive active power flow at receiving end line of IPFC for three modes which that have been gotten by simulation. Hence, these estimated values can be applied to guess initial value of VSC in IPFC and SSSC for their real modeling in power system [10-11, 13-14].

II. EASE BASIC STEADY-STATE OPERATION OF SSSC

SSSC is shown at Figure 1. Voltage source convector (VSI) of SSSC supplies ac synchronous series voltage that its phasor vector and line current *I* are shown in Fig. 2. In capacitive mode, line reactance decrease. In order to this issue, sending active and reactive power flow to end line and line current increases . In inductive mode, that its operation is opposite of capacity mode [1-2]. Then, active and reactive power flows at receiving end line are given (line resistance is not considered) as follow [3-4]

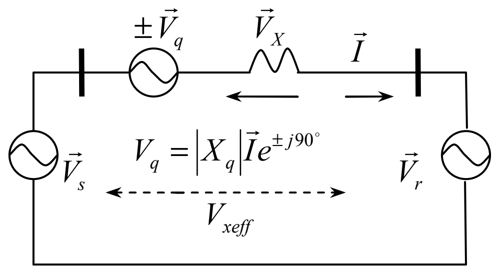

Figure 1. A single line diagram of SSSC

$$P_r = \frac{VrVs}{X}\sin(\delta) + \frac{VrVq}{X}\cos(\frac{\delta}{2}) \tag{1}$$

$$Q_r = \frac{VrVs}{X}\cos(\delta) - \frac{Vr^2}{X} + \frac{VrVq}{X}\sin(\frac{\delta}{2}) \tag{2}$$

Where $\varphi_1 + \varphi_2 = \delta$

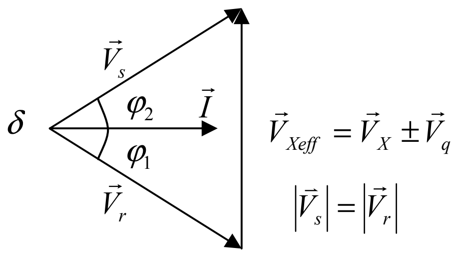

Figure 2. Phasor diagram of SSSC

In Fig.1 $Vxeff$ is total of dropped voltage of line reactance and injecting voltage VSI of SSSC. In real system, maximum phase angle between of sending-end voltage source and, a receiving-end voltage source is 15°. Therefore, injected active power of VSI of SSSC is greater than its injected reactive power, because [1-2].

$$P_{SSSC} = \frac{VrVq}{X}\cos(\frac{15}{2}) = 0.99\frac{VrVq}{X} \tag{3}$$

$$Q_{SSSC} = \frac{VrVq}{X}\sin(\frac{15}{2}) = 0.13\frac{VrVq}{X} \tag{4}$$

First of all, observe that injecting reactive power of VSI respect to its injecting active is considerably less. Accordingly, while grid needs to decrease its stray reactive power, SSSC is incapable. On the other hand, it is impossible for SSSC to control injecting active and reactive power of VSI separately [5, 8].

III. Proposed Injection Model of IPFC in Steady-State Operation

Proposed injection model of IPFC consists from two back-to-back, series connected with lines, dc to ac inverters include to two IEEE machines system is shown in Fig. 3. IPFC is considered, system 1 is main system and system 2 as auxiliary system for supplying needed active and reactive power of VSI1 in system 1 [6, 12].

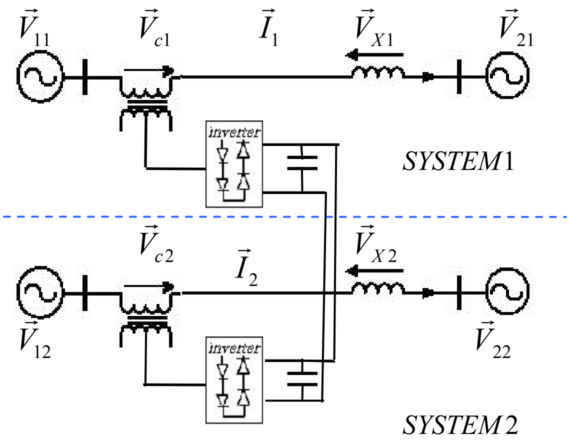

Figure 3. A single line diagram of IPFC

Therefore, equations of injecting active and reactive of power of VSI1 based on proposed injection model in system 1 are as follows:

$$P_{r1} = \frac{V_{11}V_{21}}{X_1}\sin\delta_1 + \frac{V_{21}V_{c1}}{X_1}\sin(\varphi_{21} + \varphi_{c1}) \tag{5}$$

$$Q_{r1} = \frac{V_{11}V_{21}}{X_1}\cos\delta_1 - \frac{V_{21}^2}{X_1} + \frac{V_{21}V_{c1}}{X_1}\cos(\varphi_{21} + \varphi_{c1}) \tag{6}$$

The significant effect of this model is emerged in equations (5) and (6). Indeed, this equations can be used for exact linear model of operation of IPFC involves three mode, resistive, capacitive and inductive in power system. Therefore, it is shown in following.

A. IPFC in Resistive mode

Object in resistive mode of IPFC is decreasing reactive power flow to 0 P.U and increasing real power flow at receiving end line to 1 P.U in this case, can be established that

$$Q_{r1} = 0 \tag{7}$$

$$I_1 = I_{1p} \tag{8}$$

Where $I_1 = I_{1p} + jI_{1q}$.

B. IPFC in capacitive mode

Principal privilege of IPFC in this mode is apparent in improving the aforesaid problems of SSSC. In this way, by providing simultaneous and independently compensation of needed reactive and active in system 1 by system 2, can lead system 1 to maximum active power transfer ability and control reactive power flow in system 1. Thereby, for system 2 is given as:

$$P_{r2} = \frac{V_{22}V_{12}}{X_2}\sin\delta_2 - \frac{V_{22}V_{c2}}{X_2}\cos(\varphi_{c2} + \varphi_{22}) \tag{9}$$

$$Q_{r2} = \frac{V_{22}V_{12}}{X_2}\cos\delta_2 - \frac{V_{22}^2}{X_2} + \frac{V_{22}V_{c2}}{X_2}\sin(\varphi_{22} + \varphi_{c2}) \tag{10}$$

From (9) can be observed that injecting active power part of VSC2 is negative. It means, system 1 is supplied by power VSC2 of system 2 as auxiliary system.

C. IPFC in inductive mode

In some conditions, inductive mode of IPFC is used to approach to minimum value of injecting active power and decreasing of injecting reactive in system 1 simultaneously

$$P_T = P_{r1} + P_{c1} \rightarrow$$

$$MIN\ (P_T) = MIN\ (P_{r1} + P_{c1}) \rightarrow$$

$$MIN\ (P_T) = (P_{r1} - P_{c1}) \rightarrow -\frac{\pi}{2} \le \varphi_{c1} < 0 \tag{11}$$

Where P_T is sending active power to end line.

Therefore we can use (9), (10) and (11) to find sending active and reactive to end line in system1. Operation region of IPFC in system 1 is between –π / 2 and to 0 and because of system 2 that supplies system active power demanding, therefore capacitive region of system 2 tends to between –π / 2 to - π. For system 2 we have

$$P_{r2} = \frac{V_{22}V_{12}}{X_2}\sin\delta_2 - \frac{V_{22}V_{c2}}{X_2}\sin(\varphi_{c2} - \varphi_{22} - \frac{\pi}{2}) \tag{12}$$

Reactive power flow is similar to capacitive mode, can get from equation (12).

IV. CASE STUDY

The proposed method has been tested by IPFC and SSSC operation for IEEE two machines system in Fig. 3 [13]. The simulation is based on resistive mode, capacitive mode and inductive mode. The buses of two systems were assumed ideal. The voltage of two system generators are 1 P.U with a 30° and line reactance is 0.5 P.U [13].

A. Resistive mode

In this case, the voltage phasor, V_{c1} with a magnitude of 0.134 P.U is injected at –30°, so [P_{r1}, Q_{r1}], change from [1.0, -0.2681] P.U to [1.0, 0] P.U and [P_{r2}, Q_{r2}] lead to [0.866, -0.53] P.U from [1.0, -0.2681] P.U. Therefore, equations (5), (6) and (8) are used for numeral estimating this mode. Result of resistive mode compare with simulation result that shown in TABLE I.

TABLE I. REACTIVE AND ACTIVE POWER FLOW ESTIMATION OF SYSTEM 1, 2 IN RESISTIVE MODE

Resistive Mode	Simulation	Proposed method	%Error
P_{r1}	1	1.00019	0.02
Q_{r1}	0	0	0
P_{r2}	0.866	0.86619	0.021
Q_{r2}	-0.53	-0.5356	1.45

B. Capacitive mode

For capacitive mode, voltage phasor V_{c1} with a magnitude of 0.26 P.U is injected at +45°, the values of [P_{r1}, Q_{r1}], with an ideal lossless system, change to [1.5, -0.1341] P.U the values of [P_{r2}, Q_{r2}] is kept at [0.866, -0.53] P.U For estimating this mode equations (5), (6), (9), (10) applied. The results have been shown in TABLE II.

TABLE II. REACTIVE AND ACTIVE POWER FLOW ESTIMATION OF SYSTEM 1, 2 IN CAPACITIVE MODE

Capacitive Mode	Simulation	Proposed method	%Error
P_{r1}	1.5	1.52	1.35
Q_{r1}	-0.134	-0.1336	0.3
P_{r2}	0.866	0.8654	0.069
Q_{r2}	-0.53	-0.527	0.569

C. Inductive mode

The results have been shown in TABLE III. At tertiary case, a voltage phasor V_{c1} with a magnitude of 0.26 P.U is injected at -75°, the values of [P_{r1}, Q_{r1}] should change to [0.634, 0.0981] P.U as same as capacitive mode [P_{r2}, Q_{r2}] remains at [0.866, -0.53] P.U (5), (6) and (11) are used for this case and the results have shown in TABLE III.

TABLE III. REACTIVE AND ACTIVE POWER FLOW ESTIMATION OF SYSTEM 1, 2 IN INDUCTIVE MODE

Inductive Mode	Simulation	Proposed method	%Error
P_{r1}	0.634	0.632	0.315
Q_{r1}	0.098	0.099	1.01
P_{r2}	0.866	0.8654	0.069
Q_{r2}	-0.53	-0.5276	0.569

The simulation of these modes has been carried out by power system analysis tools package in MATLAB software and has been depicted in Fig. 4. The Figure shows the VSI injecting complex power of IPFC in three modes for system 1. Also, system1 line current and series injecting voltage of VSI in system 1 have been simulated observe in Fig. 5 and Fig. 6.

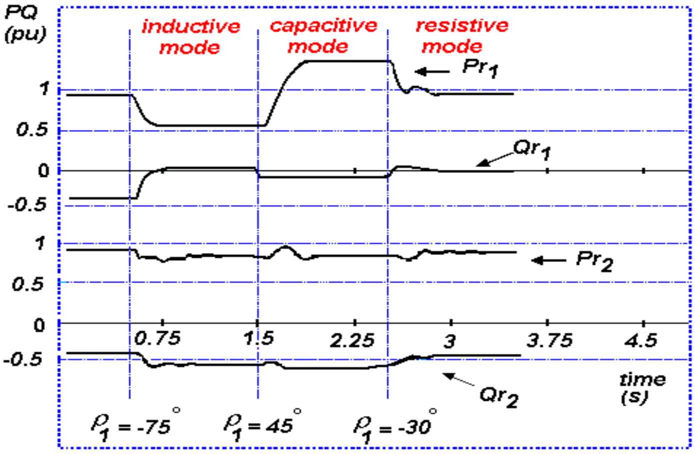

Figure 4. Real and Reactive Power in Lines 1 and 2 in three modes

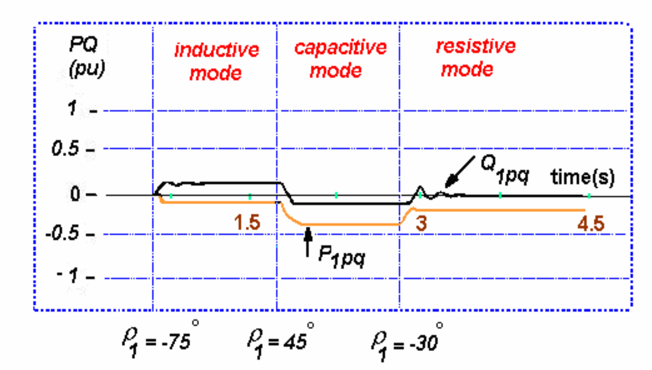

Figure 5. Behavior of injective complex power of IPFC in three modes for system 1

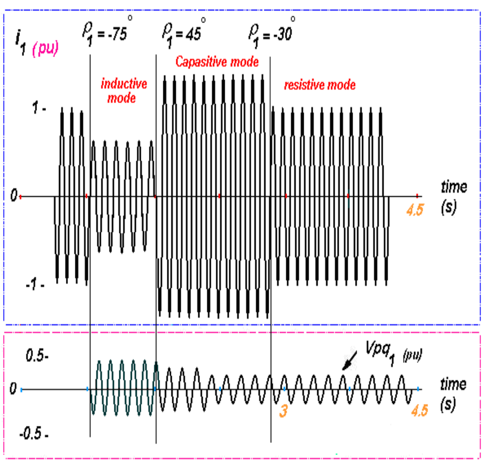

Figure 6. Waveforms of line current and injective voltage of IPFC in three modes

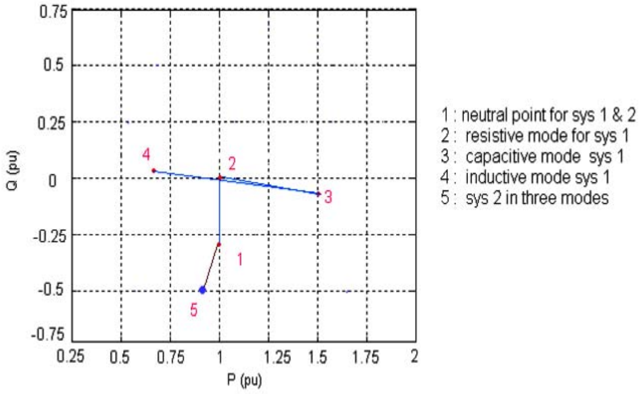

Figure 7. Operating Points of IPFC for two systems

V. CONCLUSIONS

In this paper, characteristic of SSSC and IPFC based on new injection model were considered. Firstly, linear model of voltage source inverter (VSI) of IPFC was improved. Therefore, robust equations of the active and reactive power of IPFC based on new injection model were used. Actually, for estimating of initial injected voltage and its phase angle of IPFC and SSSC for their modeling in practically manner. This model was tested in inductive, capacitive and resistive modes for IEEE two machine systems. The comparison of the result with MATLAB simulation shown that the proposed analysis estimating method in different operating point of IPFC is accurate and acceptable. In addition, this method can be extended for acquiring approximation of active and reactive power flow of receiving end line equations with transmission line resistance.

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