Interphase Power Controller Application to Mitigate Transmission Network Short Circuit Level

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Abstract. In the steady state condition, an IPC controls power flow by setting PST phase angle. In this paper, an efficient algorithm is presented to specify location and the IPC parameters as a fault current limiter including angels of phase shifting transformer (PST) and reactances of the reactor and the capacitor. As a case study, the algorithm is applied to Tehran Regional Electric Company (TREC) to reduce the Short Circuit Level (SCL) of critical transmission substations. The transient stability studies are performed in the transmission network with the installed IPC to verify the effective current limiting characteristic of IPC.

Key words

Component, IPC, Fault current limiting, Transient stability.

1. Introduction

Interconnection of large number of generating units and connection of networks may cause high Short Circuit Levels (SCL) that can exceed the interrupting capability of existing circuit breakers and associated substation equipments. Conventional methods to decrease the SCLs are:(a) separation of the system buses (split buses)[1], (b) application of current limiting equipments, like series inductors or superconducting devices and (c) upgrading of protection equipments with enough margins to handle the new SCL.

Nevertheless, the application of these measures should be done after a detailed study of the electric network performance, since deterioration is possible due to (a) increased active and reactive power losses, (b) reduction of power flow margins for steady state and (c) diminished operating reliability and flexibility. However, none of mentioned methods provide additional transmission capability or ability to control or redirect the power flow. Splitting the bus sections may mitigate the fault problem in relatively cost-effective manner, but the operating flexibility and reliability will be decreased. Getting official authorizations to change the existing bus configuration may be difficult. Series reactors can neither completely eliminate the fault currents nor effectively reduce transmission constrains. Under heavily loaded conditions, this option can cause problems for voltage regulation also. Upgrading the transmission system either by adding new lines, using existing resources efficiently, replacing the under rated circuit breakers and associated substation equipments are other options of overcoming the high SC (Short Circuit) problem, which have planning and engineering challenges.

Utilizing the IPC in power system network to reduce the fault current can be a alternative solution [2,3]. Also, IPC is one of the technologies that have been used to control the power flow in network lines. In this paper, the applications of IPC to reduce short circuit currents and improve the transient stability in Tehran Regional Electric Company (TREC) are discussed.

2. IPC Modeling

The IPC is not a new technology but it is not well known among power engineers. The working mechanisms of some types of IPCs, i.e., flexibility and speed of response put this technology in the category of FACTS devices [4,5]. A generic IPC model consists of two branches, one branch with an inductor in series with PST and the other branch with a capacitor in series with the PST (Fig. 1). For SC reduction, the reactance of the inductor and capacitor are selected to be equal (i.e., they are tuned to the fundamental frequency), so as to impose an infinite impedance to the short circuit current (SCC) only, while controlling power flow under normal and post-contingency conditions [6].

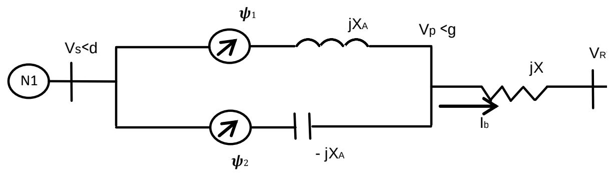

Fig. 1. IPC in series with a transmission line

Considering Fig. 1, one can derive the IPC per-unit equations, as follows [3]:

$$V_P = \frac{X}{X_A}\left[V_S\angle(\delta+\psi_1) - V_S\angle(\delta+\psi_2)\right] + V_R\angle 0 \quad (1)$$

$$I_b = -\frac{V_S\angle\delta}{X_{IPC}\angle\psi_{IPC}} \quad with \quad \begin{cases} \psi_{IPC} = \dfrac{\psi_1+\psi_2}{2} \\ X_{IPC} = \dfrac{X_A}{2\sin(\frac{\psi_1-\psi_2}{2})} \end{cases} \quad (2)$$

$$P_R = \frac{V_S V_R}{X_{IPC}}\cos(\delta+\psi_{IPC}) \quad (3)$$

$$Q_R = -\frac{V_S V_R}{X_{IPC}}\sin(\delta+\psi_{IPC}) \quad (4)$$

Supposing $\psi_1 = -\psi_2 = \psi$, (3) and (4) can be simplified, as follows:

$$P_R = \frac{2V_S V_R}{X_A}\cos(\delta)\sin(\psi) \quad (5)$$

$$Q_R = -\frac{2V_S V_R}{X_A}\sin(\delta)\sin(\psi) \quad (6)$$

If we assume $V_S = V_R = 1$, $\delta \approx 0$ and including just one PST in reactor branch ($\psi_2 = 0$ and $\psi_1 = \psi$), the above equations can be rewritten as follows:

$$P_R \approx \frac{\sin\psi}{X_A} \quad (7)$$

$$Q_R \approx -\frac{1}{X_A}\sin^2(\frac{\psi}{2}) \quad (8)$$

3. IPC Parameter Determination

In this study, it is assumed that only one PST has been installed in the reactor branch .To determine the parameters of IPC, the following algorithm has been proposed [4]:

Step1. The buses with the SCLs higher than the circuit breakers breaking capabilities are specified by running the SC analysis. Then, difference between the calculated SC and CB breaking capacity is calculated for each bus. Then, The bus with the highest difference is specified.

Step2. The line which has the highest current contribution in feeding the specified bus SCC is determined.

Step3.The load flow analysis for peak, medium and light loads conditions, is performed.

Step4. The maximum active power of the specified line is determined.

Step5. The minimum value of the X_A is determined using the inequality X_A> (10×Z_{th}) to prevent the series resonance phenomenon. Where, Z_{th} is the network equivalent impedance seen from the bus to which IPC is connected.

Step6. According to (7), the maximum phase angle variation interval of single PST is determined.

Step7. The IPC is added to the network and the new value of the substation SCL is calculated.

Step8. If the decrement of the SCL was not satisfactory, following two solutions are suggested: a) the installation of second IPC in the specified substation. In this case, second line with maximum current contribution in SCC should be selected b) if it is possible; IPC is located to split two sections of busbar. In both cases steps (3) to (7) of proposed algorithm should be repeated.

4. Allocation of IPC in TREC

According to the above-mentioned algorithm, SC analysis has been performed for TREC network in the forecasted peak load condition of year 2011. The IEC standard has been utilized to calculate the SC calculations using DIgSILENT software. To determine the most critical bus, the parameter named "Switch Utilization Factor" (*SUF*), is defined as follows:

$$SUF = \frac{I_{sc(Calculated)} - I_{sc(switch)}}{I_{sc(switch)}} \quad (9)$$

Where, $I_{SC(Calculated)}$ is the calculated bus SCL obtained by software and $I_{SC(Switch)}$ is the minimum existing CB capacity in corresponding substation. Negative value of *SUF* means there is the security margin for current breaking in bus. The positive value of *SUF* means that bus CBs capability is lower than the bus SCL. The higher positive values of *SUF* result in the more critical condition for that bus.

Table I. The positive *SUF* values in TREC (Year 2011)

Bus Name	**Bus Voltage (kV)**	**SCL (kA)**	**lowest breaking capacity of bus (kA)**	***SUF***
Montazer-Qaem	230	58	12.5	3.64
Firuzbahram	230	71	25	1.84
Besat	230	35	19.7	0.777
Firuzi	230	34	19.7	0.726
MontazerQaemCC	230	60	40	0.5
ReyGS	230	59	40	0.475
Jalal 400	400	57	40	0.425
Namayeshgah	230	37	26	0.423
Ozgol	230	32	25	0.28
DushanTapeh	230	29	25	0.16
VardAvard	230	46	40	0.15
DamavandCC 400	400	57	50	0.14
Manavi	230	28	25	0.12
NorthRey	230	55	50	0.1
RudShur 400	400	43	40	0.075
ShushTeh	230	43	40	0.075

The positive values of *SUF* in TREC buses are listed in Table I for symmetric three-phase fault. The results show that the "Montazer-Qaem" 230 kV bus has the highest positive value of *SUF*. As it can be seen, the lowest breaking capacity of the bus for the mentioned bus is 12.5 kA which is very low for a 230 kV bus and it is planned to be changed with a 40 kA CB by TREC. Consequently, the bus named "Firuzbahram 230" has the highest positive value of *SUF* and is considered as the most critical bus in 2011. Fig. 2 shows the result of SC analysis of "Firuzbahram 230" without using IPC. As it can be seen, SCL of mentioned bus is 71.23 kA. The current contribution of lines connected to this substation is listed in Table II. The results show that the "Firuzbahram – Rey Gs" 230 kV line with 10.651 kA current contribution is the first candidate to install the IPC.

Table II. Current contribution of lines connected to Firuzbahram 230kV substation

Transmission line	Feeding ratio (KA)
Firuzbahram -Azadeghan	6.295
Firuzbahram –Rey Gs	10.651
Firuzbahram -Eslamshahr	7.65
Firuzbahram -ParandR	4.74
Firuzbahram -Montazerghaem	7.03
Firuzbahram -Kan	7.81
Firuzbahram -SaeedAbad	6.901
Firuzbahram Shush	2*1.976
Transformers 400/230	4*4.061
Firuzbahram Substation SC	71.23

A. "Firuzbahram – Rey Gs" 230 kV line IPC Parameters

Based on the algorithm of section III, the parameters of IPC can be determined .The power flow results show that in peak load condition, "Firuzbahram 230" receives 228.5 MW from "Rey Gs 230 kV" power plant (Fig. (3)). Z_{th} is calculated using equation V_{OC}/I_{SC} in which V_{OC} is open circuit voltage of "Firuzbahram – Rey Gs" CB and I_{SC} is current flows through the mentioned closed CB. According to the load flow analysis, Z_{th} can be determined (Z_{th}=10.8Ω). Considering inequality $X_A>(10\times Z_{th})$, X_A has been selected to be 110Ω or $X_L=-X_C=110\Omega$. The rated capacity of the reactor and capacitance is Q=(2302/110)=480.9 MVAR. The rated capacity of PST Transformer is 300MVA which results in the maximum power flow without overloading. The maximum value of ψ can be obtained as follow:

$$\sin(\psi) = X_A(p.u.)\times P \Rightarrow \psi = 26^\circ \quad (10)$$

It should be mentioned that power flow from IPC can be controlled by changing PST phase shift angle (ψ).Fig. 4 shows SC analysis of "Firuzbahram" substation with installed IPC. As it can be seen, SCL in "Firuzbahram 230" is 64.22 kA and the current contribution of "Firuzbahram – Rey Gs" line in bus SCC is equal to zero. It means 7.01 kA decrease in substation SCL. According to step 8 of algorithm presented in section III, the second IPC can be installed in double busbar configuration of "Firuzbahram 230", IPC is utilized to split the bus in SC conditions.

Fig 5. shows the load flow analysis of Firuzbahram 230 kV with double busbar without using IPC. The maximum active power flows between two sections of bus is 149.32 MW. Using the above mentioned algorithm one can obtain the following results:

$$V_{oc} = 3.9206\,kV \text{ and } I_{sc} = 0.39\,kA \quad (11)$$

And consequently $Z_{th} = 10.052\Omega$.

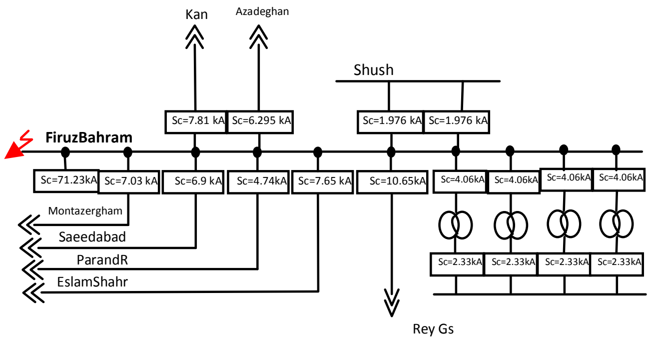

Fig. 2. SC analysis in *Firuzbahram* 400/230 kV substation

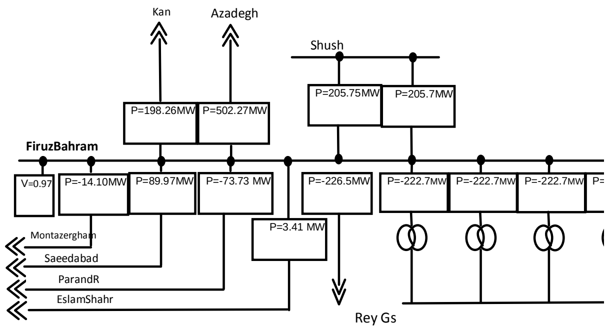

Fig. 3. Load flow analysis in Firuzbahram 400/230 kV substation

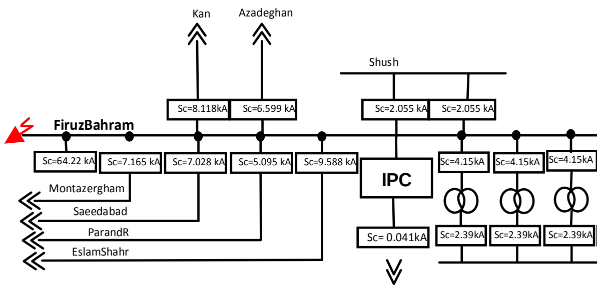

Fig. 4. SC analysis in Firuzbahram substation with IPC installed in "Firuzbahram – Rey Gs" 230 kV line

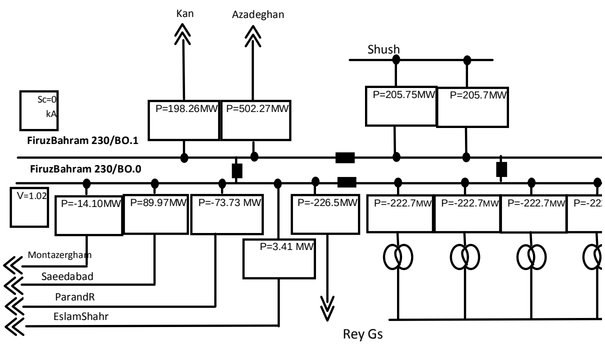

Fig. 5. Load flow analysis in Firuzbahram substation in double busbar configuration without using IPC

B. Firuzbahram 230 kV bus splitting IPC Parameters.

As it is mentioned before, X_A must satisfy the inequality $X_A > 10 \times Z_{th}$. Therefore, X_L and X_C can be considers, as follows:

$$X_A = X_L = -X_C = 105 \qquad (12)$$

Using (7), maximum phase shift of PST is ψ=17.50. Also, reactor and capacitance capacities are Q=(2302/105)≈500 MVAR. The rating of PST transformer is 300 MVA. As a result, the maximum power can flow without any overload problem. Fig. 6 represents the SC analysis results of Firuzbahram substation when the IPC is installed between bus sections. SC analysis indicates that the SCL value of one side is equal to 38.91 kA and the other side is equal to 49.74 kA. By replacing the CBs with typical 50 kA, the SC problem will be completely solved in "Firuzbahram" substation. The same fault levels could be achieved by just splitting the bus without the IPCs. However, in the case of bus splitting by IPC, the bus sections are still electrically interconnected, allowing power to flow in steady state condition between the buses through the IPC. Therefore, the original bus configuration and the operational flexibility and reliability are unchanged.

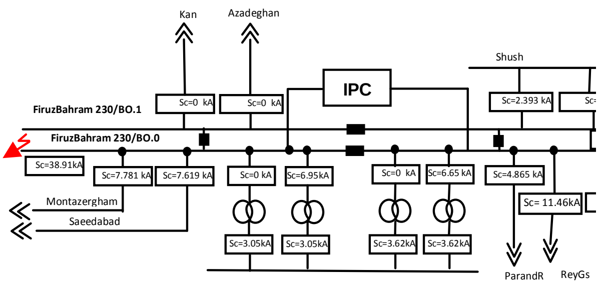

Fig. 6. SC analysis in Firuzbahram substation with an IPC used as a bus splitting device

5. Transient Stability Study

Generally, power system stability is defined as the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact [7]. Large-disturbance rotor angle stability or transient stability, as it is commonly referred to, is concerned with the ability of the power system to maintain synchronism when subjected to a severe disturbance, such as a short circuit on a transmission line. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship. The IPC can be used to improve the transient stability margins [8] ,[9]

In transient stability studies of this paper, a SC fault is applied to one of the equipments connected to a substation for 5 cycles (10 msec for f=50 Hz). Then the equipment is isolated from the network by tripping relays. To check the network transient stability, the difference of rotor angles of near power plants near faulted bus and slack power plant are studied in time domain. The power plants near to the Firuzbahram substation are listed in Table III. This study is usually repeated for all equipments around the study area. In this paper, 2 cases have been studied. In case 1, SC fault has been simulated near to the one section of the Firuzbahram 230 kV double busbar and in the second case SC fault is occurred near to the other section of 230 kV busbar. In both cases, the IPC is isolated from the network. Fig. 7 depicts the rotor angles deviations of mentioned power plants to the slack power plant of network (Abbaspoor Dam) for first case. In Fig. 8, the same parameters have been shown for the second case. As it can be seen in both cases, rotor angle deviations have been damped. It should be mentioned that the transient stability studies have been performed for the rest of equipments near to the Firuzbahram 230 kV substation but not represented in this paper.

Table III. Power plants near Firuzbahram substation

Power Plant Name	H (sec)
Montazer-Qaem St.	5
Montazer-Qaem CC	10
Ray Gs	13
Parand Gs	13
Rudshur CC	11
Rajaee St.	8
Damavand CC	13
Rajaee CC	10

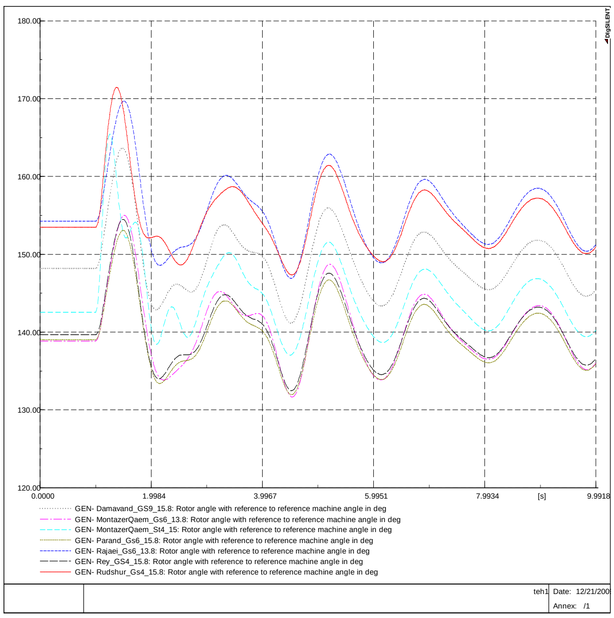

Fig. 7. Rotor angle deviations of power plants after SC fault occurrence at first section of Firuzbahram 230 kV bus

6. Conclusions

In this paper, a new method has been presented to reduce SCL of transmission buses including a new algorithm to determine the IPC location and specify its parameters. The proposed algorithm has been applied to TREC transmission network and Firuzbahram 230 kV substation has been determined as the most critical busbar. The results show the effective performance of the installed IPC between two sections of Firuzbahram 230 kV substation to reduce the determined busbar SCL without undesired effective on the transient stability of the system.

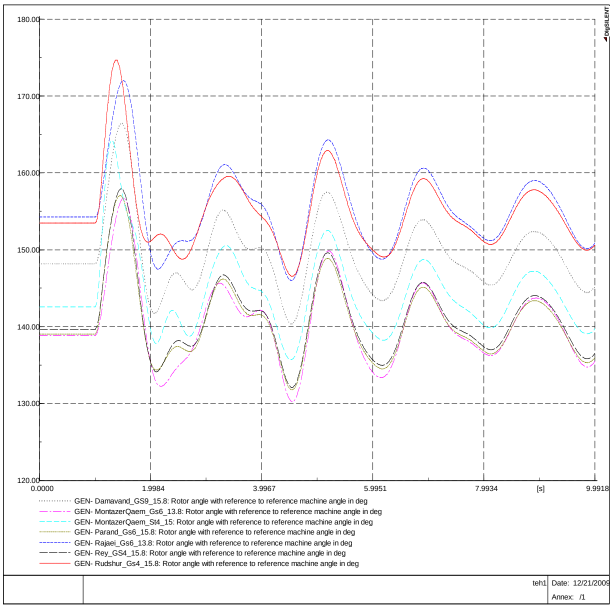

Fig. 8. Rotor angle deviations of defined power plants for SC fault near to the second section of Firuzbahram 230 kV bus with IPC outage

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