Optimal Location of IPFC That Handles Operating Constraints for Reducing Transmission Lines Utilization Levels in Electric Power Grid

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ABSTRACT

The day-to-day increase in electric energy demand with increasing population and urbanization is causing transmission facilities to transfer load at their upper limits; therefore, the probability of failures of these facilities increases. One of the ways of mitigating failures is by constructing more transmission lines; which would serve as alternatives to reduce the transmission line utilization levels (TLUL). However, there are constraints in adopting this method; therefore, the use of Interline Power Flow Controller (IPFC) has been suggested by many researchers; but very few of these studies proposed the IPFC that has capability of handling operating constraints (IPFCthC) in solving power transmission systems issues. Some of the studies that proposed the IPFCthC use trial and error approach in identifying the optimal location for its injection in multi-buses power grid. Also, some of the studies that proposed the IPFCthC do not employ it to investigate its capability in reducing TLUL. In order to reduce the TSUL in the multi-bus grid, this paper therefore proposes optimal location for the injection of IPFCthC using Transmission Line Performance Index (TLPI) and Transmission Line Reactive Power Loss (TLRPL) in Newton-Raphson Load Flow (NRLF) algorithm. The proposed algorithm was tested on IEEE-30 Test-bed in Matlab environment. The results obtained reveal that the TLUL of each of the transmission lines of the Test-bed that is not connected to PV bus is reduced averagely by 4.00 % each, with the injection of the IPFCthC in an optimally location established by the proposed algorithm.

Keywords: *Interline Power Flow Controller, Constraints, Newton Raphson load flow algorithm, Transmission Line Performance Index and Transmission Line Reactive Power Loss*

1. INTRODUCTION

The increase in power demand with increasing population and urbanization has led to over utilization of power transmission lines, and thereby made the systems to be loaded beyond their limits [1], and [2]. As a result of this, the probability of failures of transmission lines increases [3]. The approach adopted by some researchers in solving over utilization of power transmission system is to upgrade the system by constructions of new transmission lines [4]. However, there are constraints in adopting this method, the constraints are; high cost of right of way (ROW) and long duration of engineering, procurement and construction activities [5]. For instance, in a fair terrain, it takes minimum of four years to complete a 330 kV double circuit, 70-80 km transmission line [5]. For example, in Nigeria, several MW of the generated power are not being evacuated due to insufficient transmission capacity [6]. In order to minimize this economic loss and meet the energy demand of the country, the National Integrated Power Projects (NIPP) awarded contracts for the construction of several kilometres of transmission lines [6], [7], and [8]. Several years after the award of the project, less than 20 % of the projects are yet to be delivered due to ROW issues; this is as a result of issues arising from the communities. Thus, the court has ordered prohibitory injunctions in several sections of the lines [9].

It has been suggested in [7] that the use of a member of Flexible Alternating Current Transmission System (FACT) device, Interline Power Flow Controller (IPFC), will reduce the overall system utilization with no ROW issues. But the electric power grid (EPG) comprises of several transmission lines; therefore, the optimal location of IPFC becomes an issue. To that effect, [10], [7], and [11] developed and proposed algorithms using Disparity Line Utilization Factor (DLUF) and Multi-objective Differential Evolution; Genetic Algorithm (GA) Technique; and DLUF respectively, to optimally place the IPFC so as to manage congestions in EPG. For the sake of improving voltage stability in EPG, [12] also proposed a GA-GSA hybrid procedure for the optimal placement of IPFC in multi-bus power grid. However, the contributions of [10], [7], [11], and [12] did not consider IPFC

operating constraints and violation handlings. But in the case of [13], a fresh power injection model for IPFC and its adjusted state variables together with the network state variables are presented. The specified control target with IPFC practical constraints are achieved in [13] in Newton-Raphson Load Flow (NRLF). Similarly, [14] adopted the same method but with a simple proposed model for IPFC in NRLF algorithm. The results obtained in [13] and [14] show that the IPFC practical constraints can be enforced. However, in placing the proposed IPFC models by [13] and [14] in optimal locations of multi-bus test beds, so as to demonstrate their effectiveness and performances in controlling load flows, [13] and [14] used trial and error method. Also there is no test that verifies if the handled practical constraints of the proposed IPFC models can further handle transmission system utilization problems. These identified omissions are addressed in this contribution. The injection of the IPFC that has capacity of handling constraints (IPFCthC) in the existing transmission network will reduce building of more transmission lines to a very reasonable extent; and the problems associated with acquisition of ROW will be eliminated.

2. METHODOLOGY

The IPFC that has capability of handling operating constraints (IPFCthC) is modeled and incorporated in NRLF algorithm; in addition, Transmission Line Performance Index (TLPI) and Transmission Line Reactive Power Loss (TLRPL) are also embedded in the proposed model in MATLAB environment, so as to be able to find the choicest location of the IPFCthC for the purpose of reducing transmission line utilization levels (TLUL). To that effect, in line with [14], the mathematical model of the IPFC is re-constructed to obtain the violation handlings of the operating constraints, which are: series injected current of master and slave converters (M&SCs), series injected voltage of M&SCs and power exchange in the M&SCs. The simulation results obtained by using IEEE-30 Test-bed [15] are utilized in studying the efficacy of the IPFCthC model in reducing the TLUL.

2.1 Modeling of IPFCthC

An IPFC is a series-series FACT system, in which two or more Static Synchronous Series Compensators are connected via a common DC link to produce the device that controls the power transmitted in multiple lines of EPG [16]. It transfers power from lines that are heavily loaded to those that are lightly loaded; and each converter in IPFC absorbs or injects Vars individually [17], as such, the net real power is zero in IPFC.

Figure 1 shows an IPFC that comprises M&SCs coupled to an alternating current system via T_1 and T_2 transformers; and in between the M&SCs is a DC link. The master converter (MC) controls a designated apparent power S_{sp}^M that flows from bus m to bus n ; whereas, a designated real power P_{sp}^S flowing from bus m to bus h is being controlled by the slave converter (SC) [14]. It is evident from the figure that V_{se1} and V_{se2} are the injected voltage sources of the MC and SC through T_1 and T_2 respectively. If it is assumed that the net impedances at the primary circuits of T_1 and T_2 are Z_{se1} and Z_{se2} respectively; hence the equivalent circuit of Figure 1, that is, the model of IPFC that has capacity of handling constraints and violations (IPFCthC) in an EPG, is presented in Figure 2.

Figure 1 Schematic diagram of IPFC [16]

In figure 2, V_{se1} and V_{se2} are in series with Z_{se1} and Z_{se2} respectively [14]; whereas j and k buses are introduced to model the terminals of IPFCthC. In the figure too, the $I_{m,inj}$ and $I_{s,inj}$ are injection currents at buses j , and k respectively.

Figure 2 Schematic diagram of the IPFCthC model

In figure 2,

$$Z_{se1} = Z_{se1(p)} + \epsilon_1^2 Z_{se1(s)} = R_{se1} + jX_{se1} \quad (1)$$

$$Z_{se2} = Z_{se2(p)} + \epsilon_2^2 Z_{se2(s)} = R_{se2} + jX_{se2} \quad (2)$$

In equations (1) and (2), the subscripts p and s represent primary and secondary circuits of the T_1 and T_2 respectively, whereas, ϵ_1 and ϵ_2 the turns ratio of the T_1 and T_2 respectively.

2.2 Handling of Power Exchange Violation in IPFCthC

In an ideal converter, the real power provided by a converter (P_{ex1}) is supposed to be equaled to the real power extracted by another converter (P_{ex2}); provided inherent storage units are not connected, therefore;

$$P_{ex1} + P_{ex2} = \text{Re}(V_{se1} I_{se1}^*) + \text{Re}(V_{se2} I_{se2}^*) = 0 \quad (3)$$

The IPFCthC ascertains whether there is power exchange violation in MC, by comparing P_{ex1} with maximum rated real power P_{ex}^{max} of the MC viz;

$$P_{ex1} - P_{ex}^{max} = 0 \quad (4)$$

If there is power exchange violation in MC, the IPFCthC corrects it to P_{ex}^{max} ;

$$P_{ex1} = P_{ex}^{max} \quad (5)$$

And knowing that

$$P_{ex1} = \text{Re}(V_{se1} I_{se1}^*) = \text{Re}(I_{m,inj} Z_{se1} (I_{sp}^M)^*) \quad (6)$$

And upon applying Kirchhoff's Current law to bus j in figure 2;

$$I_{m,inj} = I_{sp}^M - I_{mj} = \left(\frac{S_{sp}^M}{V_j} \right) - \left(\frac{V_m - V_j}{Z_{se1}} \right) \quad (7)$$

Upon using equations (7) in (6), then;

$$P_{ex}^{max} = \operatorname{Re} \left(Z_{se1} \left(\left(\frac{S_{sp}^M}{V_j} \right) - \left(\frac{V_m - V_j}{Z_{se1}} \right) \left(\frac{S_{sp}^M}{V_j} \right)^* \right) \right) = \operatorname{Re} \left(\left(\frac{Z_{se1} S_{sp}^M S_{sp}^{M*}}{V_j V_j^*} \right) - \left(\frac{(V_m - V_j) S_{sp}^{M*}}{V_j^*} \right) \right) = \operatorname{Re} \left(\frac{Z_{se1} S_{sp}^M S_{sp}^{M*} - (V_m - V_j) V_j S_{sp}^{M*}}{V_j V_j^*} \right) \quad (8)$$

Since, $S_{sp}^M = P_{sp}^M + jQ_{sp}^M$, $V_m = V_m^{Re} + jV_m^{Im}$, $Z_{se1} = jX_{se1}$ and $V_j = V_j^{Re} + jV_j^{Im}$; therefore, in equation (8),

$$Z_{se1} S_{sp}^M S_{sp}^{M*} = jX_{se1} (P_{sp}^M + jQ_{sp}^M)(P_{sp}^M - jQ_{sp}^M) = jX_{se1} ((P_{sp}^M)^2 + (Q_{sp}^M)^2) \quad (9)$$

$$V_j V_j^* = (V_j^{Re} + jV_j^{Im})(V_j^{Re} - jV_j^{Im}) = (V_j^{Re})^2 + (V_j^{Im})^2 \quad (10)$$

$$(V_m - V_j) V_j S_{sp}^{M*} = (V_m V_j - V_j^2)(P_{sp}^M - jQ_{sp}^M) = \left\{ P_{sp}^M (V_m^{Re} V_j^{Re} - V_m^{Im} V_j^{Im} - (V_j^{Re})^2 + (V_j^{Im})^2 + 2V_j^{Re} V_j^{Im}) + Q_{sp}^M (V_m^{Re} V_j^{Im} + V_m^{Im} V_j^{Re}) \right\} + j \left\{ P_{sp}^M (V_m^{Re} V_j^{Im} + V_m^{Im} V_j^{Re}) - Q_{sp}^M (V_m^{Re} V_j^{Re} - V_m^{Im} V_j^{Im} - (V_j^{Re})^2 + (V_j^{Im})^2 + 2V_j^{Re} V_j^{Im}) \right\} \quad (11)$$

Upon using equations (9) through (11) in equation (8), we have;

$$P_{ex}^{max} = \frac{-\left\{ P_{sp}^M (V_m^{Re} V_j^{Re} - V_m^{Im} V_j^{Im} - (V_j^{Re})^2 + (V_j^{Im})^2 + 2V_j^{Re} V_j^{Im}) + Q_{sp}^M (V_m^{Re} V_j^{Im} + V_m^{Im} V_j^{Re}) \right\}}{(V_j^{Re})^2 + (V_j^{Im})^2} \quad (12)$$

Upon expressing Q_{sp}^M as the subject of the formula, we have:

$$Q_{sp}^M = \frac{P_{ex}^{max} \{ (V_j^{Re})^2 + (V_j^{Im})^2 \} + \left\{ P_{sp}^M (V_m^{Re} V_j^{Re} - V_m^{Im} V_j^{Im} - (V_j^{Re})^2 + (V_j^{Im})^2 + 2V_j^{Re} V_j^{Im}) \right\}}{(V_m^{Re} V_j^{Im} + V_m^{Im} V_j^{Re})} \quad (13)$$

Equation (13) represents the reactive power that will be dispatched from the master line so as to take care of P_{ex1} usurpation. Similarly, if there is violation in SC in figure 2, the IPFCthC corrects it to P_{ex}^{max} ; and the reactive power that will be dispatched from slave line so as to take care of P_{ex2} usurpation will be

$$Q_{sp}^S = \frac{P_{ex}^{max} \{ (V_k^{Re})^2 + (V_k^{Im})^2 \} + \left\{ P_{sp}^S (V_m^{Re} V_k^{Re} - V_m^{Im} V_k^{Im} - (V_k^{Re})^2 + (V_k^{Im})^2 + 2V_k^{Re} V_k^{Im}) \right\}}{(V_m^{Re} V_k^{Im} + V_m^{Im} V_k^{Re})} \quad (14)$$

The IPFCthC mathematical expressions presented in equations (1) through (14) are incorporated into NRLF algorithm to balance the exchange of power between the converters.

2.3 Optimal Location of IPFCthC:

In the positioning of IPFCthC optimally for the purpose of reducing TLUL, there is need for minimum of two lines, which are to be connected to the same bus. In this contribution, the most loaded line is identified and the IPFCthC is placed between the line and any line connected to the same bus as the most loaded line and being the least utilized [10]. The degree of utilization of a line is determined in this contribution via TLPI, and this determines the location of one converter. In accordance with [18], the TLPI is defined as loading intensity of a transmission line under normal and abnormal conditions, and can be expressed as

$$TLPI_{mj} = \frac{\omega_{mj}}{2\alpha} \left(\frac{MVA_{mj}}{MVA_{mj(\max)}} \right)^{2\alpha} \quad (15)$$

In equation (15), $TLPI_{mj}$, $MVA_{mj(\max)}$ and MVA_{mj} denote the TLPI, maximum MVA rating, and actual MVA of the transmission network that connects bus m to bus j respectively. In the model, ω_{mj} is a non-negative weighted factor which indicates importance of line $m-j$; whereas, α is an exponent. In this contribution, α and ω_{mj} for all the lines are assumed to be 2 and 1 respectively.

In this contribution, in order to optimally place the second converter of the IPFCthC so as to reduce TSUL, we consider all the transmission lines that are connected to the same bus with most utilized line which is identified by

TLPI. The second bus of the lines that have point of common connection (PCC) with the line having the highest TLPI must not be a PV or swing bus. A line with the highest reactive power loss value among the lines at the PCC with most utilized line is to be taken as the position of the second converter of the IPFCthC.

2.4 Implementation of IPFCthC Model In NRLF Algorithm For Positioning IPFCthC Optimally For Reducing TLUL

The procedure of positioning IPFCthC optimally for the sake of reducing transmission lines utilization levels in electric power grid is

Step 1: Read the line and bus data of the EPG

Step 1b: Read the maximum operating constraints data of the two converters

Step 2: Develop the admittance matrix, and let the iteration number = 0.

Step 3: Evaluate Jacobian matrix, and mismatch vector

Step 4: Obtain the load flow in the EPG subjected to constraints

Step 5: Update the buses and converters voltages

Step 6: Has load flow converged? If the answer is NO, increase iteration by 1, and go to step 3

Step 7: Has a constraint of IPFCthC violated? If the answer is YES, go to step 1

Step 8: If the answer to question in step 7 is NO, evaluate the TLPI of all the lines

Step 9: Choose the most utilized line having the highest TLPI value

Step 10: Choose a transmission line with the highest reactive power losses value among the transmission lines at a PCC with most utilized line

Step 11: Insert IPFCthC between the most utilized line and the identified line in step 10

Step 12 - Validate by re-calculating the utilization of the lines

3. SIMULATION RESULTS AND DISCUSSION

The simulation results of the TLUL of the IEEE-30 test bed without and with IPFCthC are presented in this section of the paper. The test bed is presented in Figure 3.

Figure 3 The line diagram of IEEE-30 Test-bed [15]

For the test bed, and in line with [14], the reactance of the transformers that coupled converters of IPFCthC to master and slave lines are taken to be $0.1 p.u$ each, and the convergence tolerance as 10^{-8} with the base apparent power of 100 MVA; whereas I_{se}^{max} , V_{se}^{max} , and P_{ex}^{max} are taken as 10, 1 and 1 respectively. In this contribution, in

line with [10], any line connected to *PV bus* is not utilized; therefore, TLPI for those lines are not evaluated and are assumed to be zero as shown in Table 1.

Table 1 Transmission Line Performance Index

From -To	TLPI without IPFCthC	TLPI with IPFCthC	% TLUL Reduction	From -To	TLPI without IPFCthC	TLPI with IPFCthC	% TLUL Reduction	From -To	TLPI without IPFCthC	TLPI with IPFCthC	% TSUL Reduction
1-2	0.0000	0.0000	-	4-12	0.4402	0.4221	4.11	21-23	0.0068	0.0065	4.41
1-3	0.0000	0.0000	-	12-13	0.0000	0.0000	-	15-23	0.0515	0.0495	3.88
2-4	0.0000	0.0000	-	12-14	0.0815	0.0783	3.93	22-24	0.0651	0.0625	3.99
3-4	0.8236	0.7899	4.09	12-15	0.1887	0.1814	3.87	23-24	0.0220	0.0212	3.64
2-5	0.0000	0.0000	-	12-16	0.0826	0.0794	3.87	24-25	0.0209	0.0201	3.83
2-6	0.0000	0.0000	-	14-15	0.0165	0.0158	4.24	25-26	0.0426	0.0409	3.99
4-6	0.7437	0.7131	4.11	16-17	0.0423	0.0407	3.78	25-27	0.0474	0.0455	4.01
5-7	0.0000	0.0000	-	15-18	0.0655	0.0630	3.82	28-27	0.1775	0.1703	4.06
6-7	0.3821	0.3665	4.08	18-19	0.0316	0.0304	3.80	27-29	0.0641	0.0616	3.90
6-8	0.0000	0.0000	-	19-20	0.0695	0.0668	3.88	27-30	0.0728	0.0700	3.85
6-9	0.3265	0.3132	4.07	10-20	0.0941	0.0905	3.83	29-30	0.0375	0.0360	4.00
6-10	0.1623	0.1556	4.13	10-17	0.0669	0.0643	3.89	8-28	0.0000	0.0000	-
9-11	0.0000	0.0000	-	10-21	0.2174	0.2090	3.86	6-28	0.1893	0.1815	4.12
9-10	0.2868	0.2756	3.91	10-22	0.0656	0.0631	3.81	-	-	-	-

Table 1 reveals that the most utilized line is the line that connects bus 3 to bus 4 with 82.36 % utilization. Therefore, one of the converters of the IPFCthC is connected to the line. The other converter has to be connected between a line having either bus 3 or bus 4 as one of the two buses. It is evident from the Figure 3 that only one line is connected to bus 3, and that is, the line 3-1. This cannot be the other line for the second converter of the IPFCthC, because bus 1 is the swing bus. In case of bus 4, Figure 3 reveals that there are three lines that are connected to it; the lines 4-2, 4-6 and 14-12. However, bus 2 is a PV bus; therefore, the line 4-2 is excluded from the probable lines. The remaining two lines are lines 4-6 and 4-12. After evaluating the reactive power losses of the two probable lines, lines 4-6 and 4-12 have 1.179 MVars and 4.685 MVars respectively. This shows that the second converter should be coupled to the line 4-12; therefore, the optimal placement of the converters of the IPFCthC is between lines 4-3 and 4-12; where $m = 4$, $j = 3$ and $k = 12$.

In this study, the IPFCthC controls the designated real and reactive power that flows through the master line; and only the designated real power that flows through the slave line. Seven scenarios are simulated as shown in Table 2.

Table 2 IPFCthC parameters for seven case scenarios for IEEE-30 Test Bed

IPFCthC Parameters with Different Specified Values And Injected Loads									
Case	P_{sp}^M (MW)	Q_{sp}^M (MVA)	P_{sp}^S (MW)	V_{se1} (p.u)	Θ_{e1} (deg)	P_{ex1} (MW)	V_{se2} (p.u)	Θ_{e2} (deg)	P_{ex2} (MW)
1	10	1.5	10	0.0422	67.70	0.0026	0.1007	-78.48	-0.0026
2	20	1.5	10	0.0517	70.51	0.0053	0.1007	-78.50	-0.0053
3	20	2.5	10	0.0519	69.46	0.0059	0.1007	-78.50	-0.0059
4	20	-1.5	10	0.0512	73.73	0.0034	0.1007	-78.49	-0.0034
5	25	0.0	10	0.0562	73.01	0.0057	0.1007	-78.50	-0.0057
6	-20	-1.5	15	0.0138	48.28	-0.0022	0.0954	-78.46	0.0022
7	25	-5.0	-15	0.0556	77.99	0.0020	0.1271	-78.48	-0.0020

The series converters voltages, and active powers exchanged in the two converters are evaluated. The IPFCthC ensures that the total real power dispatched (positive values) by a converter is equalled to the total real power exacted (negative values) by the other converter.

After optimal placement of IPFCthC in the test bed, its effect on the state of utilization is re-evaluated by calculating the LUFs of each line. It can be seen from Table 1 that, though the IPFCthC is placed between only two lines, the loading of the whole system is reduced. Each of the utilization levels of the transmission lines of the test-bed that is not connected to swing and PV buses is reduced by 4.00 % on average.

Figure 4 Percentage TLUL of IEEE-30 Test bed before and after placement of IPFCthC

Figure 4 shows the line utilization of the transmission lines of the test bed before and after the placement of the IPFCthC device in an optimal location. The transmission lines having either the slack bus or any of the PV buses are not plotted in the graph.

4. CONCLUSION

This paper has shown that TLPI and reactive power losses can be employed to identify optimal location for the injection of IPFCthC for the purpose of reducing TLUL instead of its arbitrary placement in the power grid.

The IPFCthC helps in utilization management in power transmission networks; even if trial and error method is used in placing it as demonstrated in [14]; where an IPFCthC is tested on IEEE-30 test-bed by arbitrarily placing it in lines 6 -10, and 6 - 28. It is however found in this contribution, that the locations chose by [14] are not the optimal locations for the efficient utilization management using IPFCthC with two converters. With the IPFCthC, the optimal location using TLPI and reactive power losses concept as proposed in this contribution, are found to be between the lines located between buses 4 and 3, and buses 4 and 12. With this, the overall reduction of system utilization on the test bed is found to be greater than the arbitrary placed IPFCthC by [14].

Constructions of new transmission networks in order to reduce transmission networks' utilization levels normally result in unbearable cost, and the difficulty in obtaining ROW, which is associated with community and court issues. These issues and many others normally lead to too much delay in execution of transmission networks project; it is therefore, recommended that ministries of power and energy in developing economies need to review the existing development plans of reducing transmission networks' utilization levels by considering IPFCthC in all planning and implementation stages. This will be more effective, if such important device is considered and incorporated into their power networks.

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CONFLICT OF INTEREST STATEMENT

The authors state emphatically and authoritatively that they have unknown vying fiscal interests or individual affinities that could have seemed to influence the work reported here.

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