Optimal Location of Facts for ATC Enhancement

M. W. Mustafa, R. O. Bawazir

Abstract*— *According to the changes in power structure (deregulation), competitive markets became in urgent need to have ability to satisfy the rise of energy demands. However, it is limited by the existing transmission grids; therefore, the markets pay attention to have efficient utilization of the current transmission system that comes through the Available Transfer Capability (ATC) which is computed using proposed technique named by Repeated Power Flow (RPF). In order to have improvement in ATC, Flexible AC Transmission System (FACTS) devices are used to control power flow (PF), thus improve the power profile in the transmission system. In this paper, two types of controllers are used Static Synchronous Compensator (STATCOM) and Unified Power Flow Controller (UPFC). The insertion of the controller in the power system comes through determining the particular location in the transmission system; the proposed method for optimal position is called Loss Sensitivity Index (LSI). This paper is applied on 5, 14 and 24 Bus Test Systems and simulated in Power system Analysis Toolbox (PSAT) software. The proposed methods have yielded results in improvement of ATC.

Index Terms*— *ATC, LSI, RPF, STATCOM, UPFC.

I. INTRODUCTION

Nowadays, power system encounters several new challenges according to the energy conversion of some countries from regulating power system structure into deregulating structure in a reliable and economic power supply perspective. It is thought that the heightened number of potential producers patronized by the consumers is considered as major defining role for the success of a competitive market. However, with this good conversion in the power system, the transmission lines in an open market have experienced certain restrictions in order to establish the expansion of transmission grids that will be subjective to defining factors such as environment concerns, right of way, cost consuming time and so on. Since electricity serves as an essential commodity, the markets have been prompted to developing a mode of improvement called Available Transfer Capability (ATC) which is calculated via the Independent System Operators (ISO) and posted on Open Access Same Time Information System (OASIS) [1],[2]. In order to enhance ATC, it should control the Power Flow (PF) parameters through a Flexible AC Transmission System (FACTS).

Numerous researches have been focused on establishing the optimal location of FACTS and ATC computation either by presenting them together at the same time or they are analyzed individually.

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According to [3], UPFC was located in power system according to the sensitivity of the total system real power loss and shown improved voltage stability. In [4], FACTS control was placed based on the Saddle-Node Bifurcation where P-V curve represents the weakest bus in the system while CPF was employed in calculating ATC as in [5]. In [6], the optimal location of SVC was determined by Genetic Algorithm while ATC was calculated using repeated RPF that resulted in the improvement of the voltage profile. Similarly, [7] focused on ATC enhancement based on the Optimal Power Flow (OPF) to attain the highest transfer capability with interfacing to FACTS control, where line and voltage limits were considered. In [8], the Thyristor Controlled Series Compensator (TCSC) was applied to enhance the transfer capability of the power network of incorporating reactive power flow in ATC based on power transfer distribution factors (PTDF); the location of TCSC is in all lines per test. Studies carried out by [9] revealed that the insertion of Static Synchronous Series Compensator (SSSC) in power systems are based on the solution of OPF for ATC which estimates the Maximum Load Increase (MLI) for DC models while solving MLI for each location of the SSSC in the network, building order lists and decreasingly sorted with the top elements representing the most suitable candidate lines. The main objective of this paper is to develop and simulate the optimal location of two types of FACTS used; Static Synchronous Compensator (STATCOM) and Unified Power Flow Controller (UPFC) in the power system by using Loss Sensitivity Index (LSI) method. The change in power system profile by using controllers results in the increase of ATC calculated based on the proposed Repeated Power Flow (RPF).

II. ATC

ATC is defined as an efficient tool for determining how much extra power can be transferred between the source and load at a specified time for specific set of conditions in physical transmission lines to further enhance the commercial activity above already committed uses [10]. By employing any method to compute ATC, it is not sufficient to ensure that ATC's value is the maximum unless PF parameters are controlled. The obtained value of ATC is periodically updated, since it is function of the parameters which depend on the condition of the power system [7]. Since the power is directional by nature, calculated ATC from area A to area B is not same as from area B to area A. ATC can be represented mathematically as follow; ATCTTCTRMCMBETC (1) Total Transfer Capability (TTC) is defined as in [12]. Transmission Reliability Margin (TRM) is defined as in [13]. Capacity Benefit Margin (CBM) is defined as in [14]. Existing Transmission Commitments (ETC) is the base case when the power flow solution is generated without increasing the power transfer as in Fig 1 [15]. In this paper, TRM and CBM are considered to be zero, so the equation (1) becomes; ATCTTCETC (2)

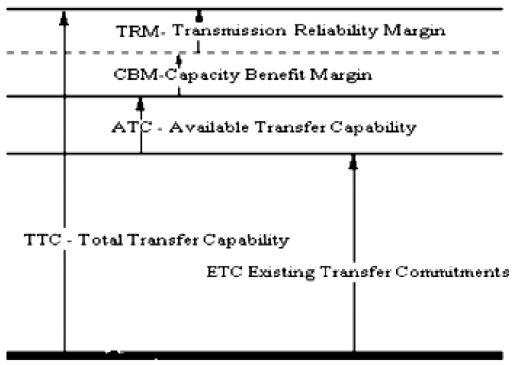

Fig 1: Concept of ATC.

III. RPF

RPF is one of the recommended techniques that are used to compute the ATC. In RPF method, load flow equations are computed repeatedly by boosting the complex power at the load with uniform load distribution factor and power factor at each load bus in the sink area while boosting the injected real power at generator bus in the source area till limits are presented [16],[17]. This can be delineated as follows;

i. Read Network System data (Lines, generators, Transformers and etc.).
ii. Solve PF using Newton Raphson method and check limits as below:

$$V_{i,\min} \leq V_i \leq V_{i,\max} \quad (3)$$

$$S_{ij} \leq S_{ij,\max} \quad (4)$$

$$P_{Gi} \leq P_{Gi,\max} \quad (5)$$

$$G_{Gi,\min} \leq Q_{Gi} \leq Q_{Gi,\max} \quad (6)$$

In respect to equation (3), it represents the voltage V_i at the bus i with maximum and minimum limits while equation (4) is the apparent power flow S_{ij} at the line it is considered as thermal limit. Equations (5) and (6) represent the real power P_{Gi} and reactive power Q_{Gi} with their maximum and minimum limits. If there is no limit or violation, go to next step.

iii. Make a step increase in λ till the limits occurred, the increase for λ must be equal for the complex load and real power source, Compute equations;

$$P_{Gi} = P^{o}_{Gi}\ 1+\lambda \quad (7)$$

$$P_{Di} = P^{o}_{Di} +\ 1+\lambda \quad (8)$$

$$Q_{Di} = Q^{o}_{Di} +\ 1+\lambda \quad (9)$$

Where P^{o}_{Gi} and Q^{o}_{Di} are the base case value (λ=0) for real generator and reactive load respectively. Go to step ii and check, if the limits occurred, stop increasing in λ and the last value of λ is maximum transfer capability in the system. After RPF is done, then TTC and ATC are ready to be calculated by;

$$TTC = \sum_{i\in \sin k} P_{Di}\ \lambda_{\max} \quad (10)$$

$$ATC = \sum P_{Di}\ \lambda_{\max} - \sum_{i\in \sin k} P^{o}_{Di}\ \lambda_{\max} \quad (11)$$

Where

$\sum P_{Di}\ \lambda_{\max}$ is the sum of load in sink area when $\lambda = \lambda_{\max}$

$\sum P^{o}_{Di}$ is the sum of load in sink area when $\lambda = 0$.

IV. FACTS

During the last century, Electro Mechanical Device (EMD) has been used to control the PF parameters; line reactance, angle and voltage bus. EMDs such as switched capacitors, inductors banks and phase-shifting transformers have some defects to reduce the performance of its own functionalities. The type of those devices are not just operating slowly, but also cannot be switched frequently in fast time, because they tend to wear out quickly [18].
New approach of devices is represented called FACTS. These devices are related to the developing in semiconductor technology. FACTS allow avoiding the drawbacks in EMD and give opportunities to improve the power flow solution, because they have ability to control more than one PF parameter with very fast response [18]. The usage of FACTS is very restricted in order to have full utilization. There are three factors should be considered;

1) Type of the device.
2) Optimal setting of each selective device.
3) Optimal location of the selective device.

A. STATCOM

Static Synchronous Compensator (STATCOM) is one of the best shunt controller in FACTS family. It is designed based on the Voltage Source Converter (VSC). The function of VSC is to produce synchronous voltage of fundamental frequency. That permits to have controllable phase angle and voltage magnitude. STATCOM is connected to the PQ bus through step-down transformer as shown in Fig 2. This FACTS device has the ability to absorb or inject reactive power from or to the bus system; hence the voltage magnitude of the bus can be set at desired value. This is known as Voltage Source Model (VSM) or Power Injection Model (PIM) [19].

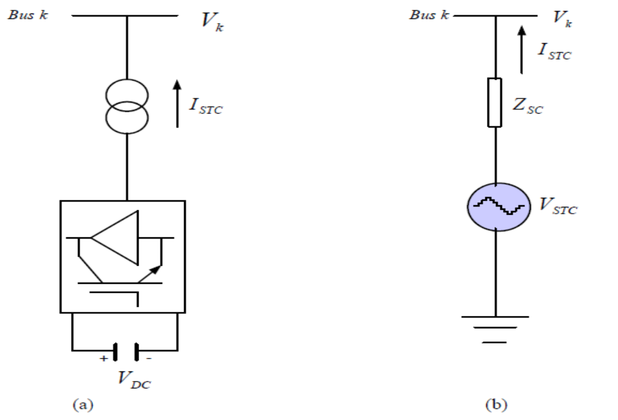

Fig 2: STATCOM diagram: (a) STATCOM

Schematic diagram (b) STATCOM equivalent circuit. In above Fig 2 for (a) and (b), V_k represents bus k voltage and V_{stc} represents the voltage source inverter. I_{stc} is the inverter's current while Z_{stc} is the transformer's impedance.

B. UPFC

Unified Power Flow Controller (UPFC) is one of the most powerful FACTS devices, because it has the ability to control the three parameters of power flow either simultaneously or separately. It is designed as shunt and series controllers based on Voltage Source Inverter (VSI). Each part of UPFC shunt and series are connected to the power system through step-down transformer. The two parts of UPFC are connected by D.C capacitor as in Fig 3.

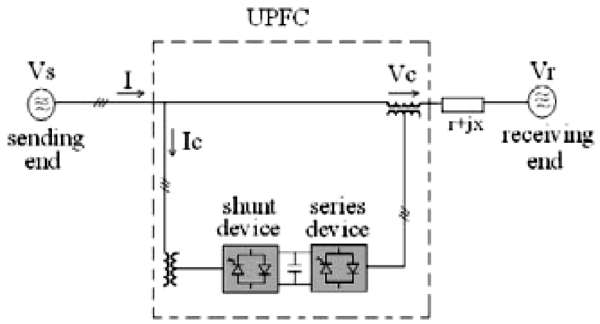

Fig 3: Voltage source model of UPFC

According to the series inverter, it is worked to inject phase voltage V_{se} the controllable phase angle and magnitude are in series with line in order to control real and reactive PF of the transmission line. So, the role of this inverter is to exchange the complex power with the line. The real power is sent to dc terminals while reactive power is supplied by the series inverter electronically. The shunt inverter part of UPFC is worked as to demand this dc terminal power either positive or negative from the line, this way allows the voltage across the capacitor V_{dc} constant. That result the absorbing power from transmission line by FACTS device is just equalized to the inverters and their transformers losses. The rest of shunt inverter capacity can be utilized to have exchanging for reactive power with the line and that leads to provide voltage regulation at connecting point [20].

The UPFC with its two inverters can operate as two FACTS devices by separating the dc side. So the series inverter acts as SSSC which generates or absorbs reactive power in order to regulate the current flow, thus PF will be enhanced in transmission line. The shunt inverter can act as STATCOM [20].

V. PLACEMENT STRATEGY OF FACTS

It should be clear that, only one of FACTS devices is permitted per component of the system. Any type of FACTS devices is placed in random Bus or line of interconnected power system; it could enhance the power flow at that particular Bus or line. However, FACTS devices can be fully utilized if optimal location is determined through specific techniques. The transfer power is restricted to the line limits or weak Buses. By ranking Buses or lines, the controller device is located at first components of ranking list [21].

Shunt controller should be installed to the PQ Bus. In case, the ranking of Buses is showed that PV (Bus No 1) and slack Bus (Bus No 2) are the weakest Buses in the system, then Bus 3 is considered the suitable location of shunt device of the ranking list. These guidelines of shunt device can be implemented for shunt–series device regarding to the shunt part of the controller.

VI.LSI

LSI is used to reduce of the total power loss in the system, improving transfer capability and enhancing the system profile in term of voltage and power flow. LSI based on reduction is used to obtain optimal location of FACTS.

a. LSI for STATCOM

LSI is equation that is derived from general total loss reactive equation of the whole system [22]-[24]. The derived equation is based on the parameters of STATCOM as represented as follows;

$$P_L = \sum_{j=1}^{N}\sum_{i=1}^{N}\left[\alpha_{ik}\ P_jP_k + Q_iQ_k\ + B_{jk}\ Q_jP_k + P_iQ_k\ \right] \tag{12}$$

$$\alpha_{jk} = \ r_{jk}/V_jV_k\ \cos\ \delta_j - \delta_k \tag{13}$$

$$\beta_{jk} = \ r_{jk}/V_jV_k\ \sin\ \delta_j - \delta_k \tag{14}$$

P_L is the real power transmission loss of the system. r_{jk} is the real part of the jk^{th} element of line impedance where j indicates sending bus number while k indicates receiving bus number. V_j , δ_j and V_k , δ_k are the complex voltages at j^{th} and jk^{th} buses, respectively. P_i and P_k are the real power injected at bus-j and bus-k, respectively. Q_i and Q_k are the reactive power injected at bus-j and bus-k, respectively. For each bus-i, sensitivity index can be expressed as,

$$a_i = \ \partial P_L/\partial Q_i\ = 2\sum_{j=1}^{NB}\ \alpha_{jk}Q_i + \beta_{jk}P_j \tag{15}$$

b. LSI for UPFC

LSI is the equation that is derived from the general total loss reactive and real power equations of the whole system [25]. The derived equation based on the parameters of UPFC can be shown as follows:

$$b_k = \ V_i - V_j\cos\ \delta_i - \delta_j\quad X_k/R_k^2 + X_k^2\ + V_j \\ \sin\ \delta_i - \delta_j\ \left(R_k/R_k^2 + X_k^2\right) \tag{16}$$

c. Criteria for Placement of UPFC and STATCOM

The criteria for optimal location for UPFC and STATCOM based on LSI can be explained as below:

- ➢ STATCOM must be located at PQ bus which has the most negative LSI based on equation (12). Slack and PV buses are discarded. Since the setting parameters of the FACTS device will be restricted to the parameters of non-load bus. Besides that, placing the device in these two buses would produce unexpected results in the power flow solution according to PSAT software requirements.

- UPFC must be placed at the most positive LSI over the all lines. The transmission line with transformer is discarded. It is noted that, UPFC is shunt-series devise, thus the shunt part of UPFC should follow same instructions for STATCOM since STATCOM is shunt device.

The entire methodology of this paper can be shown in Fig 4. It represents all steps are used in this paper.

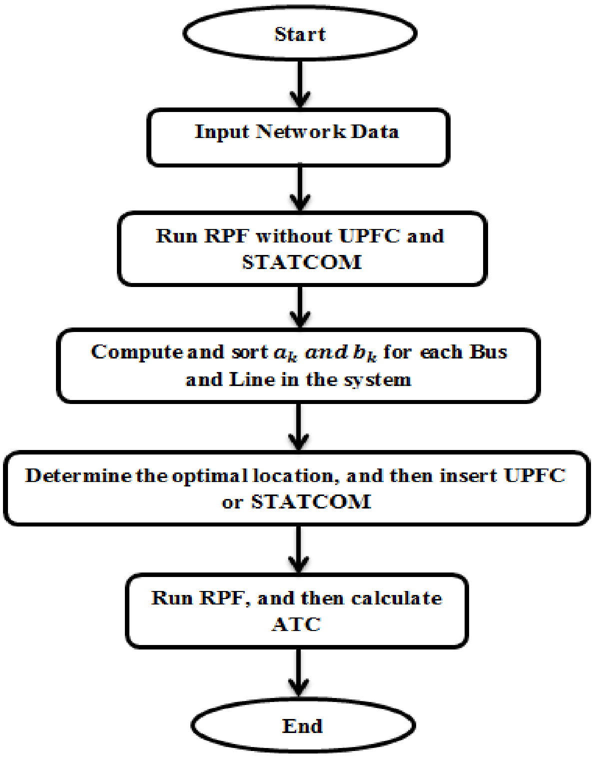

Fig 4: Flow chart of methodology

VII. CASE STUDY

ATC was computed for three simulated power system; 5, 14 and 24 Bus Test Systems. The simulations were conducted in two phases; without FACTS and with FACTS (UPFC and then STATCOM) for each system, then the results were observed. The used Power System Analysis Toolbox (PSAT) software is open source MATLAB which has many features, including PF, models of STATCOM and UPFC [26],[27]. With These features of PSAT, RPF was run and the results analyzed.

1) 5 and 14Bus Test Systems

5-Bus Test System is illustrated in Fig 5. The system is studied under different cases with respect to UPFC and STACOM. The optimal locations based on LSI for the two controllers with desired line and Bus is depicted in Table 1. RPF is performed by starting from the Base case PF and then increasing for all the complex loads and real generators by a factor λ until limit or violation of system is incurred. The active power profile is shown in Fig 6. It shows how much UPFC or STATCOM enhance the RPF, λ_{max} for UPFC and STATCOM and also ATC are depicted in Table 1. Similarly, with 14-Bus Test System, the determination of optimal location and ATC are shown in Table 2 while real power flow profile is depicted in Fig 7.

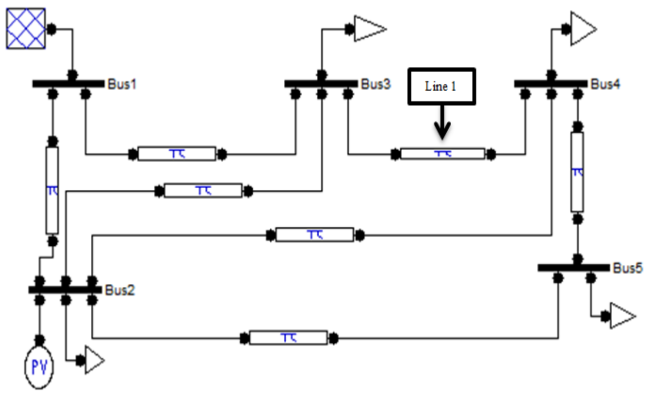

Fig 5: 5-bus system

Table 1: 5-Bus system with UPFC and STATCOM

UPFC			
LSI	Line NO.	λ_{max}	ATC (MW)
0.258991	1	2.1	617.8417
STATCOM			
LSI	Bus NO.	λ_{max}	ATC (MW)
-0.00118	3	2.0	581.6312

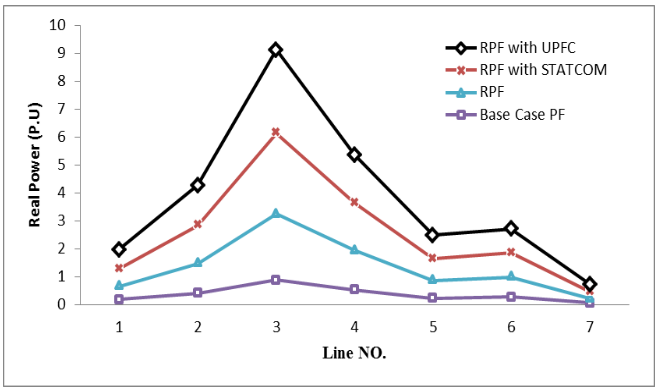

Fig 6: 5-Bus system for Active power profile with and without FACTS

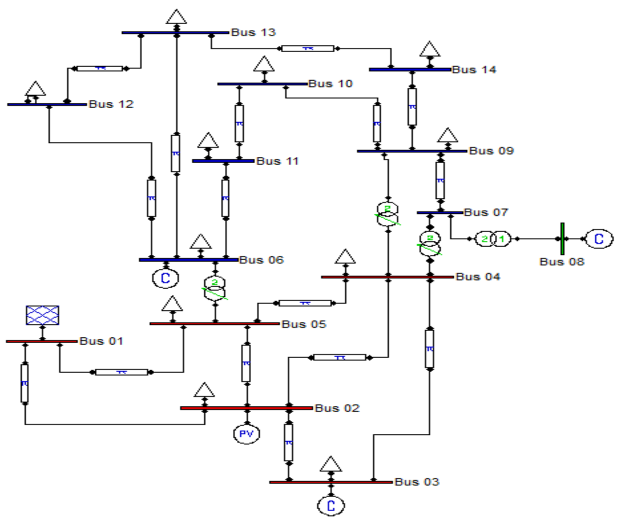

Fig 7: 14- Bus Test System.

Table 2: 14-Bus system with UPFC and STATCOM

UPFC			
LSI	Line NO.	λ_{max}	ATC (MW)
0.7020019	10	0.1	48.9451
STATCOM			
LSI	Bus NO.	λ_{max}	ATC (MW)
-0.01444	14	0.05	24.1348

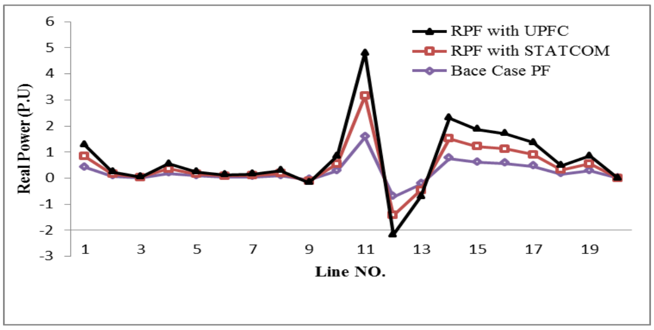

Fig 8: 14-Bus system for active power with and without FACTS.

2) *24Bus Test System*

The system is tested under different cases with respect to UPFC and STACOM regarding to single transaction between one load and generator. The optimal location based on LSI for the two controllers with desired line and Bus is depicted in Table 3. RPF is performed by starting from the Base case PF and then increasing (step by step) the complex load (at bus 20) and real generator (at bus 18) by a factor λ until limit or violation of system is reached. The active power profile is shown in Fig 9. It shows how much UPFC or STATCOM enhance the RPF, λ_{max} for UPFC, STATCOM and also ATC are depicted in Table 3.

Table 3: 24-Bus system with UPFC and STATCOM

UPFC			
LSI	Line NO.	λ_{max}	ATC (MW)
1.5998	19	0.65	476.3856
STATCOM			
LSI	Bus NO.	λ_{max}	ATC (MW)
-0.03734	19	0.6	357.5845

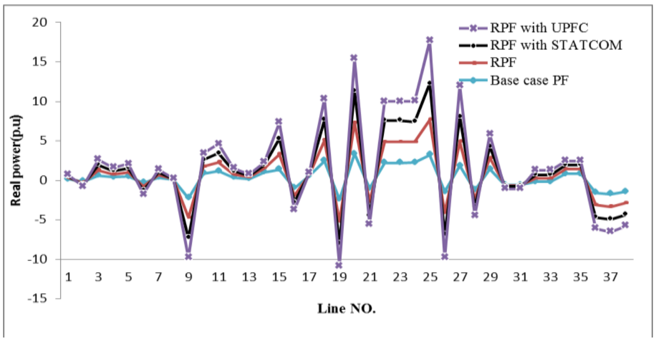

Fig 9: 24-Bus system for active power profile with and without FACTS.

VIII. CONCLUSION

The calculating of ATC using RPF indicates that maximum transfer capability in the power network when the PF parameters are controlled. STATCOM and UPFC are used to enhance ATC to attain an almost maximum value. The two devices are installed at optimal location in the power system based on the LSI method. Placing these two devices allow getting good functionality of FACTS to control the parameters of the system. Based on the obtained results, UPFC has the ability to attain better performance in term of ATC than STATCOM due to it is capability to control more than one parameters of power flow. The settings of UPFC and STATCOM in PSAT software are done by adjusting in the representing block for each device.

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