FAST AND EFFICIENT METHOD TO ASSESS AND ENHANCE TOTAL TRANSFER CAPABILITY IN PRESENCE OF FACTS DEVICE

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ABSTRACT

This paper presents the application of Genetic Algorithm (GA) to assess and enhance Total Transfer Capability (TTC) using Flexible AC Transmission System (FACTS) devices during power system planning and operation. Conventionally TTC is assessed using Repeated Power Flow (RPF) or Continuation Power Flow (CPF) or Optimal Power Flow (OPF) based methods which normally uses Newton Raphson (NR) method and the enhancement of TTC is done by optimally locating FACTS devices using an optimization algorithm. This increases the CPU time and also limits the search space hence resulting in local optimal value in TTC. To eliminate this drawback, in this paper a novel procedure using the optimization algorithm (GA) is proposed which simultaneously assess and enhance Total Transfer Capability (TTC) in presence of FACTS. Also power flow is performed using Broyden's method with Sherman Morrison formula instead of NR method, which reduces the CPU time further without compromising the accuracy. To validate the proposed method, simulation test is carried on WSCC 9 bus and IEEE 118 bus test system. Results indicate that the proposed method enhances TTC effectively with higher computational efficacy when compared to that of conventional method.

KEYWORDS: *FACTS Device, Genetic Algorithm, Power System Operation and Control, Total Transfer Capability*

I. INTRODUCTION

According to NERC report [1], Total Transfer Capability (TTC) is defined as the amount of electric power that can be transferred over the interconnected transmission network in a reliable manner while meeting all defined pre and post contingencies. Available Transfer Capacity (ATC) is a measure of transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses. It is well known that the FACTS devices are capable of controlling voltage magnitude, phase angle and circuit reactance. By controlling these, we can redistribute the load flow and regulate bus voltage. Therefore this method provides a promising one to improve TTC [2-7].

The optimal location and settings of FACTS devices for the enhancement of TTC is a combinatorial analysis. The best solutions to such type of problems can be obtained using heuristic methods. The basic approach is to combine a heuristic method with RPF [8] or CPF (Continuation Power Flow) [9-10] or OPF (Optimal Power Flow) [11] method to asses and enhance TTC. From the literature available it is understood that in all these approaches heuristic methods are used only for finding the optimal location and/or settings of FACTS devices to enhance TTC, but the value of TTC is computed using conventional methods like CPF, RPF or OPF based methods [12-20] which takes much computational time because of the following reasons. TTC should be computed accurately as well as with less computational time because of the following reasons:

First, from [21] it is evident that in operation of a power system, ATC or TTC is done for a week and each hour for a week has a new base case power flow. A typical TTC calculation frequency according to western interconnection report [22] is

- Hourly TTC for the next 168 Hours : Once per day
- Daily TTC for the next 30 days : Once per week
- Monthly TTC for months 2 through 13: Once per month.

Second, due to the fact of uncertainty in contingency listing, forecasted load demand etc even after a careful study in planning of power system and optimally locating these FACTS devices and its settings to enhance TTC the results may not be optimal during different power system operating conditions. Once when these FACTS devices are located, its location cannot be changed but the settings of these FACTS devices can be adjusted to obtain a maximum TTC for different power system operating conditions. This is again a problem of combinatorial analysis with a number of FACTS devices present in the system and with the wide range in its operating parameters.
Hence for the above reasons and with the known solution methods [12-20] to asses and enhance TTC in presence of FACTS, very high computational time is needed, which may not be a drawback during planning of power system but has an adverse effect in the operation stage.
In [23-24] TTC is computed with OPF based Evolutionary program(EP), in which EP is used to find the location, setting of FACTS devices and simultaneously it searches the real power generation, generation voltages and real power load. This method can be used in both planning and operation of a power system but the major drawback in this method is that the length of chromosome, which increases with the power system size there by increasing the computational time for getting global optimal results. Further the load distribution factor and power factor of loads in the system has not been maintained constant.
In this paper Genetic Algorithm with power flow using Broyden's method [25-26] with Sherman Morrison formula (GABS) is proposed to assess and enhance TTC in presence of FACTS which effectively enhances TTC and reduces the computational time to a great extent during planning and operation of power system. The results are compared with the conventional method Genetic Algorithm with Repeated Power Flow using NR method (GARPFNR).
The remaining paper is organized as follows: Section 2 deals with FACTS devices modelling and TTC problem formulation using GARPFNR. Section 3 gives the description about the proposed method. Section 4 deals with the Results and Discussion and finally conclusion are drawn in Section 5.

II. FACTS DEVICES AND TTC FORMULATION USING GARPFNR

In this paper the mathematical formulation for TTC with and without FACTS device using RPFNR method from [2] is combined with GA i.e. GARPFNR [18] to enhance TTC. Though there are many heuristic methods which can be combined with RPFNR to enhance TTC using FACTS, GA is used in this paper because these are best suited for optimization problems which do not possess qualities such as continuity, differentiability etc. This works on the principle that the best population of a generation will participate in reproduction and their children's called as offspring's will move on to next generation based on the concept of "survival of the fittest". Hence in this paper GARPFNR is compared with the proposed method GABS. The TTC level in normal or contingency state is given by:

$$TTC = \sum_{i \in \sin k} P_{Di}(\lambda_{\max}) \quad (1)$$

and ATC neglecting TRM, ETC is given by

$$ATC = \sum_{i \in \sin k} P_{Di}(\lambda_{\max}) - \sum_{i \in \sin k} P_{Di}^{0} \quad (2)$$

where

$\sum_{i\in \sin k} P_{Di}(\lambda_{\max})$ is the sum of load in sink area when $\lambda = \lambda_{\max}$.

$\sum_{i\in \sin k} P_{Di}{}^{0}$ is the sum of load in sink area when $\lambda = 0$.

Therefore the objective function is

$$\text{maximize TTC} = \sum_{i\in \sin k} P_{Di}(\lambda_{\max}) \quad (3)$$

Subject to

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n} P_{lossij} = 0 \quad (4)$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{n} Q_{lossij} = 0 \quad (5)$$

$$V_{i\min} \le V_i \le V_{i\max} \quad (6)$$

$$S_{ij} = S_{ij\max} \quad (7)$$

$$P_{Gi} \le P_{Gi\max} \quad (8)$$

2.1. Power Flow in GARPFNR

In GARPFNR method the power flow equations are solved repeatedly using NR method by increasing the complex load at every load bus in the sink area and increasing the injected real power at generator bus in the source area until limits are incurred the computational time will be more. In general NR method finds $'x'$ iteratively such that

$$F(x) = 0 \quad (9)$$

In the iterative process, say in m^{th} iteration $'x'$ is updated as given below

$$x^{m+1} = x^{m} - \Delta x \quad (10)$$

and $$\Delta x = -(J^{m})^{-1} F(x^{m}) \quad (11)$$

where J^{m} is the Jacobian matrix.

Since the power flow equations are solved repeatedly, for every step increment of λttc there are more than one number of iteration and for every iteration a Jacobian matrix of size n × n is computed and then inverted. For 'n' non linear equations, computation of Jacobian matrix elements includes computation of n^2 partial derivatives and 'n' number of component functions. Therefore n^2 + n functional evaluations need to be done. Again inversion of an n × n Jacobian matrix using Gauss Jordan elimination method requires n^3 arithmetic operations. The representation of chromosome in GARPFNR assuming one TCSC and one SVC at a time is shown in Fig 1.

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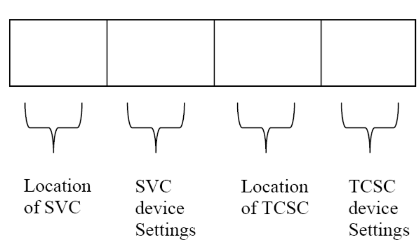

Fig 1. Representation of Chromosome

2.2. Computational Time in GARPFNR

For example let us consider a case in which GARPFNR has a population size of 30 and number of generation is 100. For each chromosome let us say it takes 10 steps in steps of 1MW of load and generation increments to compute the loading factor λ_{max} , and for each increment say a NR power flow of 3 iterations takes 1.5 sec, then for 30 chromosomes and 100 generations with 10 contingencies conditions the total time required to complete one transfer will be approximately 125 hrs. The accuracy of results can be improved by decreasing the step size at the cost of increase in computational time i.e. if the step size is decreased by a factor 10 (from 1MW to 0.1 MW) then the time for computation increases by the same factor 10.

III. DESCRIPTION OF THE PROPOSED METHOD

In this method power flow model of FACTS device and mathematical formulation of TTC is same as that of GARPFNR method but the chromosome representation and power flow procedure differs as discussed below:

3.1. Power Flow in GABS

In this Broyden's method with Sherman Morrison formula is used for solving power flow. Broyden's method is a Quasi–Newton method. The starting point of Broyden's method is same as NR method i.e. an initial approximation x^0 is chosen to find $F(x^0)$ and x^1 is calculated using the Jacobian J^0. From the second iteration this method departs from NR by replacing the Jacobian matrix with an equivalent matrix 'A' which is given by

$$A^m = A^{(m-1)} + [(F(x^m) - F(x^{m-1}) - A^{m-1}(x^m - x^{m-1})] \tag{12}$$

and

$$x^{m+1} = x^m - (A^m)^{-1} F(x^m) \tag{13}$$

henceforth the number of functional evaluations is reduced to 'n' from 'n^2 + n'. Further the n^3 arithmetic operation for computing the inverse of A^m matrix can be reduced to n^2 operations using the Sherman Morrison formula as shown below as

$$(A^m)^{-1} = \frac{[A^{(m-1)}]^{-1} + U}{\Delta x^T [A^{m-1}]^{-1} \Delta F(x)} \tag{14}$$

Where

$$U = \{\Delta x - [A^{m-1}]^{-1} \Delta F(x)\} * \{\Delta x [A^{m-1}]^{-1}\} \tag{15}$$

3.2. Modified Chromosome Representation

As in GARPFNR method population is initialized randomly and each chromosome in the population consists of decision variables for FACTS device location, device settings, and objective function value and apart from that it consist of λ_{ttc} value. The value of λ_{ttc} for each chromosome is

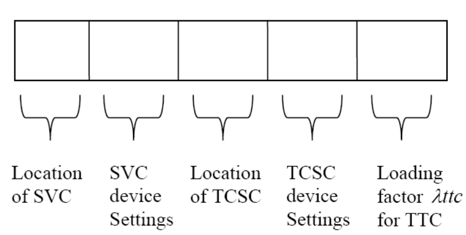

Fig. 2. Modified representation of Chromosome

fixed within a range between '0' to '1' (for an increase up to 100% in loading factor) or '0' to '2' (for an increase up to 200% in loading factor) which holds good for any complicated power system, since no power system even at the worst case is under utilized for more than 200% and the objective function is designed such that GA maximizes the value of λ_{ttc} subject to the satisfaction of equality and inequality constraints. This eliminates the use of RPF or CPF methods to calculate the loading factor λ_{ttc} .This is shown in Fig 2.

3.3. Computational Time in GABS

The computational time for assessing and enhancing TTC using GABS in presence of FACTS is far less when compared to GARPFNR because of two main reasons.

At first unlike GARPFNR method, GABS simultaneously finds the optimal location, settings for the FACTS devices and the loading factor λ_{max} for TTC computation by representing all these information in the chromosome.

Secondly in power flow using Broyden's method with Sherman Morrison formula the Jacobian inverse is computed only once during the first iteration for a given network topology and for the remaining iterations a rank one update is done to compute the inverse (an approximate Jacobian inverse). Due to the above fact the quadratic convergence of Newton Raphson method is replaced by super linear convergence which is faster than linear but slower than quadratic convergence. For a large scale system, computing Jacobian inverse for 'n' number of iterations with many transfer direction in a single contingency case is a time consuming process when compared to super linear convergence of Broyden's method. Hence the total time required to compute TTC with Broyden's method is less when compared to NR method.

For example let us consider the same case as that of GARPFNR which has a population size of 30 and number of generation are 100. For each chromosome let us say it takes 10 steps in steps of 1MW of load and generation increments to compute the loading factor λ_{max} , and for each increment say the power flow in GABS using Broyden's method with Sherman Morrison formula takes 4 iterations for a total time of 2 sec, then for 30 chromosomes and 100 generations with 10 contingencies conditions the total time required to complete one transfer will be approximately 17 hrs which is only 13.6 % of the computational time when compared to GARPFNR. This approach can also be applied during operation of power system by removing the information of FACTS location in the chromosome.

3.4. Algorithm for GABS

The algorithm for the proposed method GABS is given below

Step 1: Population size and number of generations is set.

Step 2: Read Bus data, line data, objectives, decision variables, minimum and maximum value of decision variables.

Step 3: Initialize the Population.

Step 4: TCSC and SVC settings and/or its set values with λ_{max} are obtained from decision variables of GA and make corresponding changes in power flow data.

Step 5: Run Power Flow using Broyden's method with Sherman Morrison formula.

Step 6: Check for convergence of Power flow and limit violations if any. *IF* there is any violations, penalize the corresponding chromosome to a very low fitness value say 1×10^{-5}. *ELSE* Fitness for the chromosome is evaluated as defined in (3). This process is repeated for all chromosomes.

Step 7: Apply genetic operators to perform reproduction and Replace Population.

Step 8: Check for maximum generation. *IF* yes go to step 9. *ELSE* go to *step 4*.

Step 9: From the final solution identify the setting and/or location of TCSC and SVC and λ_{max} to calculate TTC.

The flow chart for GABS is shown in Fig 3.

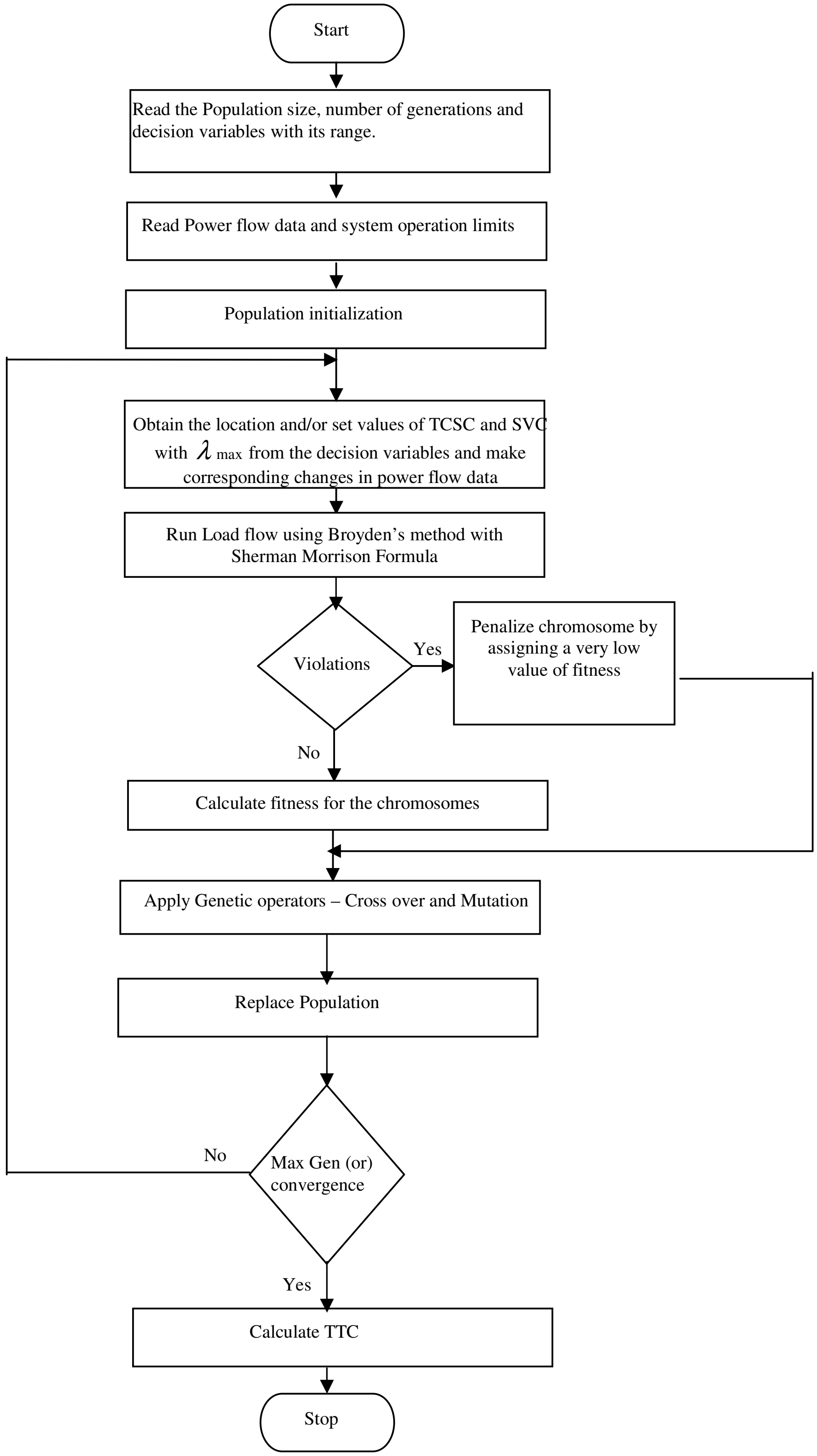

Fig 3. Flow chart for GABS

IV. RESULTS AND DISCUSSION

GABS and GARPFNR is carried out in MATLAB environment using Genetic Algorithm and Direct search toolbox and modified MATPOWER [27] simulation package in INTEL core 2 Duo CPU T5500@ 1.66 GHz processor under Windows XP professional operating system. The standard WSCC 9 bus test system and IEEE 118 bus test system [27-28] are considered to test the performance of the proposed method. Transaction between Area 1 to Area 2 alone is considered. The base value, voltage limits, SVC and TCSC limits are considered from [20]. For GABS and GARPFNR, population size of 20 and 200 generations are considered with stall generation of 20. In each of the test system two cases are considered. First case represents planning problem in which FACTS device optimal settings and location is found to enhance TTC, while the second case represents an operational problem such as change in load, unexpected contingencies etc, assuming that the FACTS devices are already located in the system, new optimal settings alone are found to enhance TTC.

4.1. WSCC 9 Bus Test System

WSCC 9 bus test system is divided into two areas. Area 1 has buses 3, 6, 8 and 9. Area 2 has 1, 2, 4, 5 and 7. Only one FACTS device in both the types (TCSC and SVC) is considered for placement.

4.1.1. Power System Planning (WSCC 9 Bus Test System)

The base case (without FACTS device) load in area 2 is 190 MW and using RPFNR method the TTC value, limiting condition and CPU time for computing this value is shown in column 2 of Table 1. Similarly with FACTS device, its optimal location and settings, TTC value, limiting condition and the computational time using GARPFNR and GABS is shown in column 3 and 4 of Table 1 respectively. It is evident that for the proposed method GABS computational time is 98.69% less and the TTC value is 0.653 % higher when compared to that of conventional method GARPFNR. The results are tabulated in Table 1.

Table 1. WSCC 9 Bus for Transfer of power from Area 1 to Area 2 (Planning)

Parameters	Without FACTS	With FACTS Device	
	RPFNR	GARPFNR	GABS
FACTS Device Setting and Location		SVC at Bus 5, Qsvc=85.45 TCSC in line 4-5, Xtcsc = - 0.3658	SVC at Bus 4, Qsvc=96.27 TCSC in line 6-7, Xtcsc =0.0845
TTC (MW)	**410.4**	**486.4**	**489.6**
Limiting Condition	Vmin at Bus 5	MVA Limit Line 1 - 4	MVA Limit Line 1 - 4
CPU Time (Sec)	**1.182**	**549.328**	**7.167**

4.1.2. Power System Operation (WSCC 9 Bus Test System)

In this case FACTS device location from the results of GABS method in 4.1.1 is considered as base case. For the operational problem, the corresponding TTC values CPU time, with and without change in FACTS device settings are tabulated in Table 2. Using GABS the TTC values for 10% increase in load, 10% decrease in load, outage of line 6 -7 and generator outage at bus 3 are 0.3%, 0.157%, 0.412% and 0.608% higher respectively and the corresponding CPU time for computation is very low when compared to that of GARPFNR method as shown in Table 2.

Table 2. WSCC 9 Bus for Transfer of power from Area 1 to Area 2 (Operation)

Parameters		Without change in FACTS device settings	With change in FACTS device settings	
		RPFNR	GARPFNR	GABS
Change in MVA Load (+ 10 %) at all Load Bus	FACTS Device Setting		Qsvc=95.39 Xtcsc = 0.3234	Qsvc=97.88 Xtcsc = 0.0934
	TTC (MW)	**440.99**	**440.99**	**442.34**
	Limiting Condition	MVA Limit Line 1 - 4	MVA Limit Line 1 - 4	MVA Limit Line 1 - 4
	CPU Time (Sec)	**1.196**	**416.911**	**3.547**
Change in MVA Load (- 10 %) at all Load Bus	FACTS Device Setting		Qsvc=99.62 Xtcsc = - 0.0212	Qsvc=99.07 Xtcsc = - 0.0943
	TTC (MW)	**490.77**	**495.9**	**496.68**
	Limiting Condition	Vmin at Bus 5	Vmin at Bus 5	Vmin at Bus 5
	CPU Time (Sec)	**1.801**	**691.923**	**4.089**
Line 6 - 7 outage	FACTS Device Setting		Qsvc=83.66 Xtcsc = - 0.4602	Qsvc=57.75 Xtcsc = - 0.4830
	TTC (MW)	**288.8**	**357.2**	**358.68**
	Limiting Condition	Vmin at Bus 7	MVA Limit Line 5 - 6	MVA Limit Line 1 - 4
	CPU Time (Sec)	**0.66**	**283.886**	**7.327**
Outage of Generator at Bus 3	FACTS Device Setting		Qsvc=100.00 Xtcsc = 0.2705	Qsvc=85.77 Xtcsc = 0.2704
	TTC (MW)	**279.3**	**279.3**	**281.01**
	Limiting Condition	MVA Limit Line 1 - 4	MVA Limit Line 1 - 4	MVA Limit Line 1 - 4
	CPU Time (Sec)	**0.634**	**173.769**	**5.553**

4.2. IEEE 118 Bus Test System

IEEE 118 bus test system is divided into two areas as shown in Table 3 and transfer of power from Area 1 to Area 2 with only one FACTS device in both the types (TCSC and SVC) is considered for placement.

Table 3 Area classification of IEEE 118 bus test system

Area	Area 1	Area 2
Bus Numbers	1 – 23, 25 –37,39 – 64, 113 –115, 117	24,38,65 – 112, 116,118

4.2.1 Power System Planning (IEEE 118 bus test system)

The total load in area 2 is 1937 MW. TTC value without FACTS device using RPFNR method is 2111.3 MW. TTC value with FACTS device using GARPFNR and GABS is 2202.8MW and 2224.3 MW respectively and the corresponding time for calculation is shown in Table 4. Hence in the proposed method GABS the time required for computation is nearly 96.77% less and the TTC value is 0.966 % higher when compared to the conventional method GARPFNR.

Table 4 IEEE 118 Bus for Transfer of power from Area 1 to Area 2 (Planning)

Parameters	Without FACTS	With FACTS Device	
	RPFNR	GARPFNR	GABS
FACTS Device Setting and Location		SVC at Bus 44, Qsvc=57.65 TCSC in line 89 - 92, Xtcsc = -0.4908	SVC at Bus 86, Qsvc= - 61.58 TCSC in line 89 - 92, Xtcsc =0.1483
TTC (MW)	**2111.3**	**2202.8**	**2224.3**
Limiting Condition	MVA Limit Line 89 - 92	MVA Limit Line 65 - 68	MVA Limit Line 65 - 68
CPU Time (Sec)	**1.259**	**308**	**9.937**

Table 5 IEEE 118 Bus for Transfer of power from Area 1 to Area 2 (Operation)

Parameters		Without change in FACTS device settings	With change in FACTS device settings	
		RPFNR	GARPFNR	GABS
Change in MVA Load (+ 5 %) at all Load Bus	FACTS Device Setting	----	Qsvc=52.89 Xtcsc = 0.5	Qsvc=54.79 Xtcsc = 0.1421
	TTC (MW)	**2359.3**	**2359.3**	**2368.8**
	Limiting Condition	Pg max at Bus 89	Pg max at Bus 89	MVA Limit Line 89 - 92
	CPU Time (Sec)	**1.59**	**402.008**	**5.992**
Change in MVA Load (- 5 %) at all Load Bus	FACTS Device Setting	-----	Qsvc= -100.00 Xtcsc = 0.2908	Qsvc=52.04 Xtcsc = 0.0876
	TTC (MW)	**1987.4**	**1987.4**	**2000.8**
	Limiting Condition	MVA Limit Line 65 - 68	MVA Limit Line 65 - 68	MVA Limit Line 65 - 68
	CPU Time (Sec)	**0.8**	**223.012**	**5.355**
Line 23 - 24 outage	FACTS Device Setting	-----	Qsvc= - 33.76 Xtcsc = -0.2061	Qsvc=36.15 Xtcsc = - 0.2179
	TTC (MW)	**1995.1**	**2150.1**	**2151.6**
	Limiting Condition	MVA Limit Line 90 - 91	MVA Limit Line 65 - 68	MVA Limit Line 65 - 68
	CPU Time (Sec)	**0.541**	**270.317**	**5.977**
Outage of Generator at Bus 61	FACTS Device Setting	-----	Qsvc=27.28 Xtcsc = 0.2890	Qsvc=99.23 Xtcsc = 0.4955
	TTC (MW)	**2246.9**	**2246.9**	**2256**
	Limiting Condition	Pg max at Bus 89	Pg max at Bus 89	Pg max at Bus 89
	CPU Time (Sec)	**1.256**	**405.674**	**6.812**

4.2.2 Power System Operation (IEEE 118 Bus test system)

In this case FACTS device location from the results of GABS method in 4.2.1 is considered as base case. For an operational problem of ±5% change in load, outage of line 23 -24 and generator at bus 61 is considered and their corresponding TTC values with and without change in FACTS device settings are tabulated in Table 5 which shows that the proposed method GABS is more efficient in assessing and enhancing TTC.

V. CONCLUSION

A fast and efficient method GABS is presented to assess and enhance TTC in presence of FACTS devices. Simulation test is carried out on WSCC 9 bus, IEEE 118 bus test system and the results are compared with the conventional GARPFNR method. From the results it is evident that the search space in the conventional method is limited due to the step increment in loading factor which results in local optimal value of TTC and use of NR method for power flow increases the CPU time due to the presence of multiple Jacobian inverses. On the other hand GABS searches the loading factor instead of incrementing it which results in near global optimal value of TTC and also the power flow is performed using Broyden's method with Sherman Morrison formula which reduces the CPU time when compared to NR method. The percentage reduction in CPU time will increase further in GABS either if the size of the system is more or when the system is lightly loaded. Hence GABS method proves to be a promising one when compared to that of conventional method.

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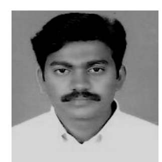

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