Chapter 2

AVAILABLE TRANSFER CAPABILITY ASSESSMENT AND ENHANCEMENT

2.1 INTRODUCTION

The recent changes in the power system structure have created renewed interest in power system operation. The open-access and deregulation made the operation of the system difficult as the power drawl and injection became open for all. This made Available Transfer Capability (ATC) estimation and enhancement an important factor both from a commercial as well as an operation point of view. In this chapter, a methodology for ATC assessment and enhancement has been proposed.

2.2 DEFINITION OF ATC AND RELATED TERMINOLOGY

The collective response of all the elements in a power system network determines the permissible power flow across various sections of lines in the network. This permissible power in the network is referred to as the **Transfer Capability** of the network. In other words, *'The Transfer Capability of the transmission network is the ability to transfer electric power when operated as a part of the interconnected power system and may be limited by the physical and electrical characteristics of the system.'*

The limits posed on the transfer of power can be thermal, voltage, or stability limits as the network operating conditions changes with time; the limiting criterion may shift among the aforementioned limits. The power transfer through the lines is governed by the minimum of the three limits.

2.2.1 Total Transfer Capability (TTC)

TTC is the amount of electric power that can be transferred over the interconnected transmission network in a reliable manner based on all of the following conditions:

1) For the existing or planned system configuration, and with normal (pre-contingency) operating procedures in effect, all facility loadings are within normal ratings, and all voltages are within normal limits.
2) The electric systems are capable of absorbing the dynamic power swings and remaining stable, following a disturbance that results in the loss of any single electric system element, such as a transmission line, transformer, or generating unit.
3) After the dynamic power swings subside following a disturbance that results in the loss of any single electric system element as described in 2 above, and after the operation of any automatic operating systems, but before any post-contingency operator-initiated system adjustments are implemented, all transmission facility loadings are within emergency ratings and all voltages are within emergency limits.
4) With reference to condition one above, in the case where pre-contingency facility loadings reach normal thermal ratings at a transfer-level below that at which any first contingency transfer limits are reached, the transfer capability is defined as that transfer level at which such normal ratings are reached.
5) In some cases, individual systems, power pool, sub-regional, or Regional planning criteria or guides may require consideration of specified multiple contingencies, such as the outage of transmission circuits using common towers or rights-of-way, in the determination of transfer capability limits. If the resulting transfer limits for these multiple contingencies are more restrictive

than the single contingency considerations described above, the more restrictive reliability criteria or guides must be observed.

2.2.2 First Contingency Incremental Total Transfer Capability (FCITTC)

FCITTC is the amount of electric power incremental above the normal base power transfers that can be transferred over the interconnected system in a reliable manner based on conditions 1, 2, and 3 of section 2.2.1.

2.2.3 First Contingency Total Transfer Capability (FCTTC)

$FCTTC$ is the total amount of electric power (net of normal base power transfers plus first contingency incremental transfers) that can be transferred between two areas of the interconnected transmission system based on conditions 1, 2, and 3 above.

$$\boldsymbol{FCTTC = FCITTC + Existing\ power\ transfer\ (Base\ case)}$$

2.2.4 Simultaneous and Non-Simultaneous transfer capability

Transfer capability is directional in nature, and in a multi-area system, each area can estimate its import and export by modeling its own system in isolation. But as far as the integrated system is concerned, this would be misleading because the component of network loading attributable to transactions between other control areas has been ignored. Further transfer capability is also heavily affected by the amount and firmness of the transaction between the control areas. Even the firm transactions may have deviations in real-time that would have to be accounted for during studies. Hence transfer capability can also be classified as simultaneous and non-simultaneous capability.

2.2.4.1 *Simultaneous Transfer Capability*

Simultaneous Transfer Capability is the amount of electric power that can be reliably transferred between two or more areas of the interconnected electric system as a function of one or more other power transfers concurrently in effect.

2.2.4.2 *Non-simultaneous Transfer Capability*

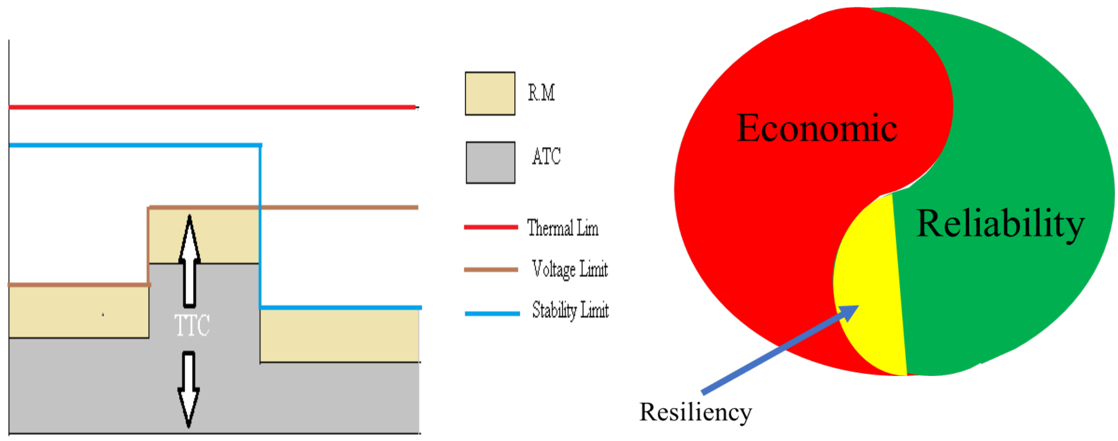
Non-simultaneous Transfer Capability is the amount of electric power that can be reliably transferred between two areas of the interconnected electric system when other concurrent normal base power transfers are held constant.

2.3 ASSESSMENT OF TRANSFER CAPABILITY

The technical challenges of computing transfer capability in electric power systems have been paraphrased by Peter W. Sauer [133]. The ATC calculation methods must: -

1) Give a reasonable and dependable indication of transfer capabilities.
2) Recognize time-variant conditions, simultaneous transfer, and parallel flows.
3) Recognize the dependence on points of injection/extraction
4) Reflect regional coordination to include the interconnected network
5) Accommodate reasonable uncertainties in system conditions and provide flexibility.

Due to the complexity involved, the assessment of transfer capability from one area to another in an interconnected system is carried out with the help of computer simulation studies. As the power system operation is taking place in real-time, the limiting condition that would limit the transfer capability would shift between different limiting conditions, namely voltage limit, stability limit, and the thermal limit.



(a) (b)

Figure 2.1 Illustration of (a) ATC TTC and R.M (b) Significance of ATC

And the transfer capability would be dictated by the minimum of these limits; the concept is graphically represented in Figure 2.1(a). The shaded area represents the transfer capability, which is the minimum of the limits among the thermal, voltage, and stability limit. The limiting condition may shift between these constraints while the system operation takes place in real-time, but the transfer capability will always be the minimum of the limits. The significance of ATC from an economic, reliability, and resiliency point of view could be visualized from Figure 2.1(b). It can be manifested that emphasizing more on economic perspective would hamper both resiliency and reliability of the system. Whereas focussing on improving reliability and efficiency would come at the cost of economic aspects. The Available Transfer Capability can be defined as total transfer capability less the capability allotted for accounting for the uncertainties in the loading of the system and other forecasted parameters in the system in addition to capability allotted for generating units to provide for their generation requirements in case of emergency.

These two constraints are referred to as Transient Reliability Margin (TRM) and Capacity Benefit Margin (CBM).

2.3.1 Transient Reliability Margin (TRM)

NERC documents define TRM as the amount of transmission transfer capability necessary to provide a reasonable level of assurance that the interconnected transmission network will be secure. TRM accounts for the inherent uncertainty in system conditions and its associated effects on ATC calculations and the need for operating flexibility to ensure reliable system operation as system conditions change. All transmission system users benefit from the preservation of TRM by transmission providers. It is the "uncommitted" transfer capability necessary to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions. It provides a reserve of transfer capability that ensures the reliability of the interconnected transmission network. The actual system conditions may change considerably in short periods of time due to operating conditions and, therefore, cannot be projected without the provision of a transfer capability margin. TRM is thus time-dependent, and generally, a larger amount is necessary for longer time horizons.

2.3.2 Capacity Benefit Margin (CBM)

As per the 1996 NERC document, Capacity Benefit Margin (CBM) is defined as that amount of transmission transfer capability reserved by load-serving entities to ensure access to generation from interconnected systems to meet generation reliability requirements. Reservation of CBM by a load-serving entity allows that entity to reduce its installed generating capacity below that which may otherwise have been necessary without interconnections to meet its generation reliability requirements. The CBM is a more locally applied margin than TRM, which is more of a network margin.

2.4 OFFLINE ASSESSMENT OF AVAILABLE TRANSFER CAPABILITY USING PATTERN SEARCH OPTIMIZATION

Available Transfer Capability is defined as the amount of power that can be transferred over and above the already committed transaction (i.e., existing transmission commitments) in the transmission network while maintaining the system constraints. Mathematically ATC can be defined as:

$$ATC = TTC - ETC - CBM - TRM \qquad 2.1$$

ATC is significant from both power system operation as well as economic point of view; as far as the economic point is concerning the appropriate information regarding ATC would enable maximum power transaction to take place maximizing the revenue, and at the same time ensuring that the system is operating within the system operating criteria.

2.4.1 Problem Formulation: - ATC Assessment

The objective of ATC evaluation is to obtain the maximum amount of power that can be reliably transferred while satisfying the system constraints. Hence the problem can be stated as a maximization problem.

$$Max(f(x)) \qquad 2.2$$

Where, $$f(x) = \sum_{j=1}^{n} x_j - \sum_{j=1}^{n} x_j^0 \;\; \forall \text{ j} \in 1,2,\ldots l \qquad 2.3$$

Subjected to

$$P_{gi} - P_{di} - \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j) \qquad 2.4$$

$$j, i \in 1,2, \dots n \ (total\ number\ of\ buses)$$

$$Q_{gi} - Q_{di} - \sum_{j=1}^{n} V_i V_j Y_{ij} \sin(\theta_{ij} - \delta_i + \delta_j) \qquad 2.5$$

$$j, i \in 1,2, \dots n \ (total\ number\ of\ buses)$$

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \qquad 2.6$$

$$i \in 1,2, \dots m \ (total\ number\ of\ generator\ buses)$$

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \qquad 2.7$$

$$i \in 1,2, \dots m \ (total\ number\ of\ generator\ buses)$$

$$V_{gi}^{min} \leq V_{gi} \leq V_{gi}^{max} \qquad 2.8$$

$$j, i \in 1,2, \dots n \ (total\ number\ of\ buses)$$

$$P_{ij}^{min} \leq P_{ij} \leq P_{ij}^{max} \qquad 2.9$$

$$j, i \in 1,2, \dots n \ (total\ number\ of\ buses)$$

Here,

Ld: Be the set representing all the load buses in the system.

l is the subset of 'Ld' load buses, which represents all the load buses in the sink area.

x_i^j is the loading (load at the j^{th} node in i^{th} iteration) in the sink area of the system.

x_j^0 is the initial loading of the j^{th} node in the sink area of the system.

The nonlinear constraints are satisfied by calling a nonlinear function k_c which maps into Newton-Raphson load flow solution algorithm and returns unity if the NR converges successfully and returns zero when Newton-Raphson fails to converge i.e.

$$k_c = \begin{cases} 1 & if\ NR\ converges \\ 0 & if\ NR\ fails\ to\ converge \end{cases} \tag{2.10}$$

$P_{gi}, Q_{gi}, P_{di}, Q_{di}$ represents active, reactive power generation injected at i^{th} bus and active, reactive power demanded at i^{th} bus. V_i is the voltage of the i^{th} bus and P_{ij} is the active power that is flowing from bus i to bus j through link ij.

The system under consideration for which ATC has to be evaluated is divided into several areas, out of which one is considered as the source area, and the other is considered as the sink. The analysis is considered at a particular loading condition for which ATC is computed accordingly. For computation, pattern search optimization is used. In the optimization process, the loads in the sink area are increased (varied), and this increment in the load is compensated by the increment in the generation of the generators in the source area. ATC is defined as the maximum increment in the load that can be provided by the generation of the source area while maintaining the system constraints. The characteristic of the load is preserved by ensuring that the power factor of the loads at the buses remains unaltered as the load is varied.

2.4.2 Solution Methodology

The technique used is diagrammatically represented in the flow chart given in Figure 2.2. The base case loading of the network considered is taken as the lower limit. The maximum limit loading of buses in the sink area is taken as the upper boundary. Generalized Pattern Search (GPS) [49] is used to generate different loading conditions corresponding to which Newton Raphson is used to obtain a solution. If the NR for the current loading is convergent, then the objective function value is evaluated. If NR does not converge, then a new pattern (loading situation) is generated using pattern search. The process is continued till the objective function is maximized.

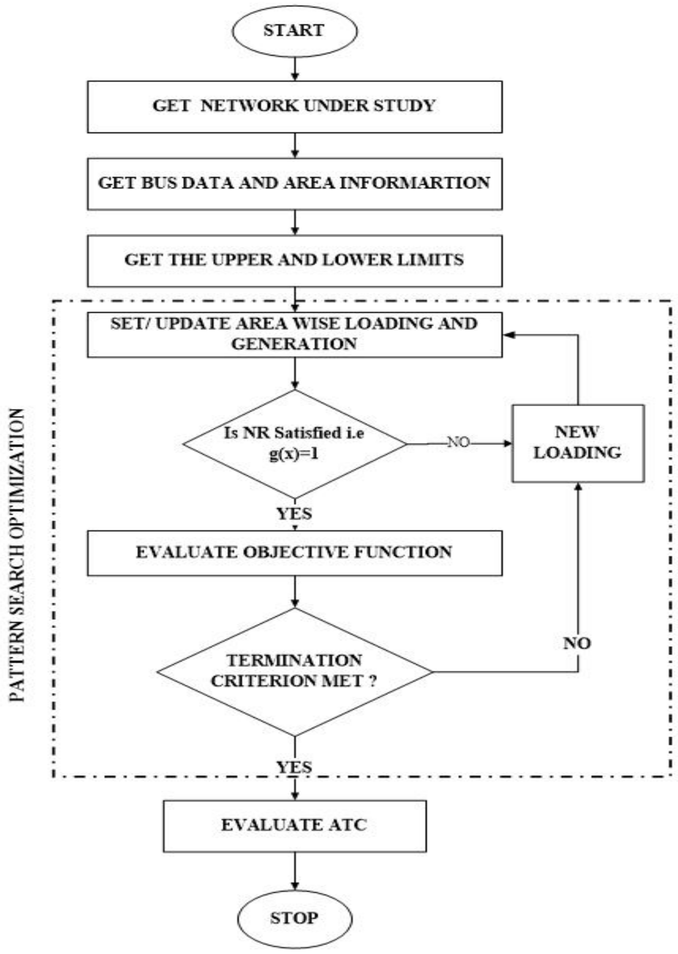


Figure 2.2 Flow Chart illustrating the solution methodology

The problem expressed by equation (2.5) through (2.10) has been solved by using the Pattern Search Optimization technique. The pattern search methodology has been explained in the next section.

2.4.3 Patter Search Optimization

Pattern Search Optimization belongs to the direct search algorithm technique. In the direct search method, the information regarding the gradient of the objective function is not required. A direct search algorithm searches a set of points around the current point, looking for the point where the value of the objective function is lower than the value of the current point. In order to understand the pattern search algorithm following terminologies is defined.

2.4.3.1 *Patterns*

A pattern is a set of vectors (v_j) used to identify the points which pattern search algorithm searches at each iteration. The set (v_j) is defined by the number of independent variables in the objective function (say N), and the positive basis set. Two commonly used positive basis sets in pattern search algorithms are the maximal basis, with $2N$ vectors, and the minimal basis, with $N + 1$ vectors. With GPS (generalized pattern search), the collection of vectors that form the pattern are fixed-direction vectors. For example, if there are three independent variables in the optimization problem, the default for a $2N$ positive basis consists of the following pattern vectors:

$$v_1 = [1\ 0\ 0] \qquad 2.11$$

$$v_2 = [0\ 1\ 0] \qquad 2.12$$

$$v_3 = [0\ 0\ 1] \qquad 2.13$$

$$v_4 = [-1\ 0\ 0] \qquad 2.14$$

$$v_5 = [0 - 1\ 0] \qquad 2.15$$

$$v_6 = [0\ 0 - 1] \qquad 2.16$$

An *N*+1 positive basis consists of the following default pattern vectors.

$$v_1 = [1\ 0\ 0] \qquad 2.17$$

$$v_2 = [0\ 1\ 0] \qquad 2.18$$

$$v_3 = [0\ 0\ 1] \qquad 2.19$$

$$v_4 = [-1\ 0\ 0] \qquad 2.20$$

With GSS (generalized search algorithm), the pattern is identical to the GPS pattern, except when there are linear constraints, and the current point is near a constraint boundary [134]. The GSS algorithm is more efficient than the GPS algorithm when linear constraints are to be handled.

2.4.3.2 *Mesh*

At each step, pattern-search searches a set of points, called a mesh, for a point that improves the objective function. Pattern-search forms the mesh by

i) Generating a set of vectors d_j by multiplying each pattern vector v_j by a scalar Δ^m , Δ^m is called the mesh size.

ii) Adding the vector d_j to the current point (i.e., the point with the best objective function value found at the previous step).

For example, using the GPS algorithm. Suppose that:

- The current point is [1.6 3.4].
- The pattern consists of the vectors

$$v_1 = [1\ 0]; v_2 = [0\ 1]; v_3 = [-1\ 0]; v_4 = [0\ -2] \qquad 2.21$$

- The current mesh size Δ^m is 4.

The algorithm multiplies the pattern vectors by four and adds them to the current point to obtain the following mesh.

$$[1.6\ 3.4] + 4 * [1\ 0] = [5.6\ 3.4]$$

$$[1.6\ 3.4] + 4 \times [0\ 1] = [1.6\ 7.4]$$

$$[1.6\ 3.4] + 4 \times [-1\ 0] = [-2.4\ 3.4] \qquad 2.22$$

$$1.6\ 3.4] + 4 \times [0 - 1] = [1.6\ 0.6]$$

2.4.3.3 *Polling*

At each step, the algorithm polls the points in the current mesh by computing their objective function values. The algorithm only computes the mesh points, and their objective function values up to the point at which it stops the poll. If the algorithm fails to find a point that improves the objective function, the poll is called unsuccessful, and the current point stays the same at the next iteration. When the Complete poll is being done, the algorithm computes the objective function values at all mesh points. The algorithm then compares the mesh point with the smallest objective function value to the current point. If that mesh point has a smaller value than the current point, the poll is successful.

2.4.3.4 *Expanding and Contracting*

Updating the mesh size Δ^m during the solution process, after each poll, is referred to as expansion or contraction. The mesh size is updated by multiplying a constant higher (km) than (for a successful poll) or less (kl) than unity (for the unsuccessful poll).

$$\Delta^m = \begin{cases} km \times \Delta^m & km > 1\ expanding \\ kl \times \Delta^m & kl < 1\ contracting \end{cases} \qquad 2.23$$

2.4.3.5 *Stopping or Convergence Criterion*

The convergence criterion for the optimization could be specified by the maximum number of iteration, mesh size Δ^m, the time duration or change in objective function value.

A schematic representation of the optimization process has been shown in Figure 2.3. The figure shows the pattern search process of two variable problems (for which four patterns are generated). The octagonal boundaries represent the mesh size; it can be seen that as the optimization process proceeds and the solution approaches the optimal value, the mesh size decrease. In iteration 1 (shown in the figure), the best function of the objective function is obtained corresponding to the pattern encircled by the circle, this point is selected, and new patterns are generated around this pattern, and this process continues till the termination criterion is met.

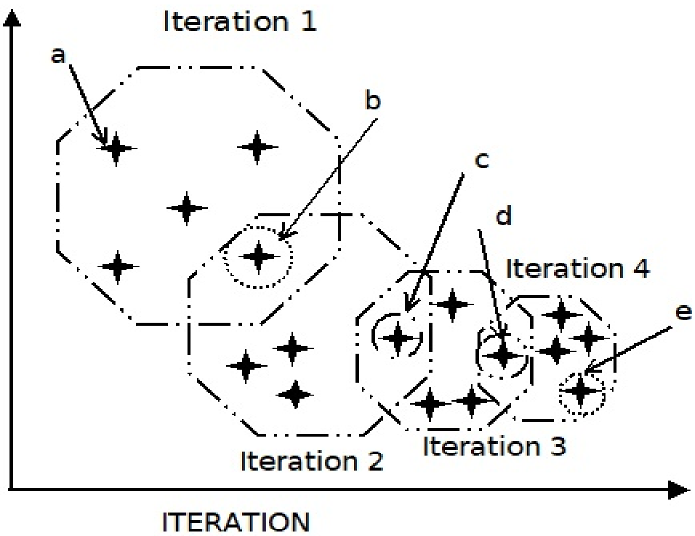


Figure 2.3 Pattern Search Optimization Process

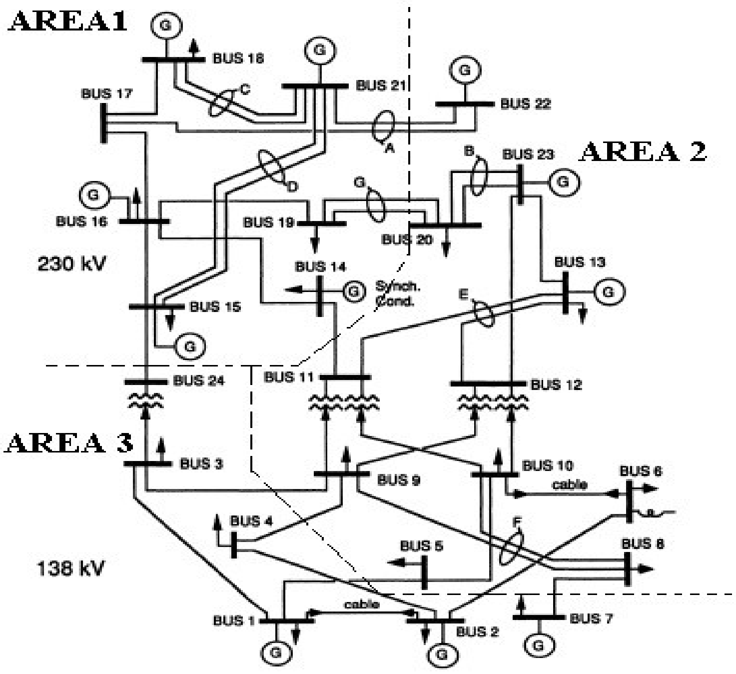


Figure 2.4 Modified IEEE 24 BUS System

2.4.4 Case Study

The proposed technique has been used to assess the ATC of the modified IEEE 24 bus RTS system and IEEE 30 bus test system. The analysis has been done in $MATLAB$ using $MATPOWER$.

2.4.4.1 *Modified IEEE 24 BUS Test system*

The IEEE 24 bus Figure 2.4 test system is modified and divided into three different areas as AREA1, AREA2, and AREA3. Table 2.1 gives the bus number categorically present in different areas along with the load in the base case, generation, and margin (the difference between the generation and load) of each area.

Table 2.2 gives the tie lines between the areas, and Table 2.3 details the modification made to the IEEE RTS 24 BUS test system [47]. The analysis of the system is done by taking CBM as 60MW; TRM has not been considered for the evaluation of ATC. The loading is increased in the sink area; this increase in the load is compensated by the increase in the generation of the source area. The loading is increased by preserving the load characteristic (power factor of loads remaining same).

Table 2.1 Areas in IEEE 24 Bus System

Area	Bus	Gen Cap MW	Load MW	Margin
1	14,15,16,17,18,19,21	1170	1125	45
2	5,6,8,9,10,11,12,13,20,22,23	1551	1141	410
3	1,2,3,4,7,24	684	584	100

Table 2.2 Tie Lines

Area	Tie Line
1 to 2	21-22,17-22,19-20(2),14-11
1 to 3	15-24
2 to 3	3-9,4-9,1-5,2-6,7-8

Table 2.3 Additional Generator Added into the system

Area	Bus	No of Generator	Gen. Cap (MW) of a single unit
1	18	1	400
1	16	2	155
1	15	1	155
2	13	1	197
3	7	1	100

Table 2.4 TTC OBTAINED USING PROPOSED METHOD FROM AREA 1 TO 2

Case	TTC level (MW)	TTC in (MW)
Normal Case	465	-
Largest Gen in Area 1 out	465	-
Largest Gen in Area 2 out	358.6359	358.6359
Line 21-22 outage	465	-
Line 19-20	465	-
Line 14-11	400	-

Table 2.5 ATC FOR TRANSACTION FROM AREA 1 TO 2 FOR RTS

Case	TTC in MW	CBM (MW)	ATC (ATC)
Area 1-2	358.6359	60	298.6359

The outage of tie lines and the largest generators have been considered for the ATC evaluation process. The proposed method is used to obtain the TTC of the considered system and the results obtained are enumerated in Table 2.4. The TTC obtained is minimum for the outage of the largest generator in area 2; hence TTC level corresponding to this value will be used to evaluate the ATC and is given in Table 2.5. In Table 2.6 and Table 2.7, the results obtained by employing the proposed method are compared with the results obtained by using transfer-based security-constrained optimal power flow (TSCOPF) [23].

Table 2.6 COMPARISION OF RESULTS OBTAINED FROM PROPOSED METHOD AND TSCOPF

Case	TTC (MW)			
	PM	TSCOPF	PM	TSCOPF
The outage of the largest generator in area 1	465	350	-	-
Outage of Largest generator in area 2	358.6359	262.8	358.6359	262.8
Outage of Line 21-22	465	350	-	-
Outage of Line 17-22	465	350	-	-
Outage of Line 19-20	465	350	-	-
Outage of Line 14-11	400	306.6	-	-

Table 2.7 COMPARISION OF PROPOSED METHOD AND TSCOPF

Case	PROPOSED TECHNIQUE (MW)			TSCOPF (MW)		
	TTC	CBM	ATC	TTC	CBM	ATC
Area 1-2	358.6359	60	298.6359	262.8	60	200.8

It can be observed from the results that TTC obtained for transactions from area 1 to 2 is minimum for the second case, with its value being 358.6359 using the proposed method and 262.8 by TSCOPF method. Similarly, ATC calculated by using the proposed method is 298.6359 while that calculated by TSCOPF is 200.8. It is seen that the proposed method evaluates ATC more than the TSCOPF.

2.4.4.2 *IEEE 30 BUS test system*

The proposed method is also applied to the IEEE 30 BUS test system taken from [47] with slight modifications, and generator locations are taken from [135]. The single line diagram of the modified IEEE 30 BUS test system is given in Figure 2.5. Table 2.8 gives the areas in the 30-bus system along with their base caseload and maximum generating capacity, and Table 2.9 gives the tie lines among different areas of the test system considered.

a) Transaction from area 1 to 2

The convergence characteristics of the pattern search optimization for transaction from area 1 to 2 for different cases is given in Figure 2.6 to. For analysis purpose in the first case of the transaction, the maximum generation of the slack bus is set equal to five times of its P^{max}.

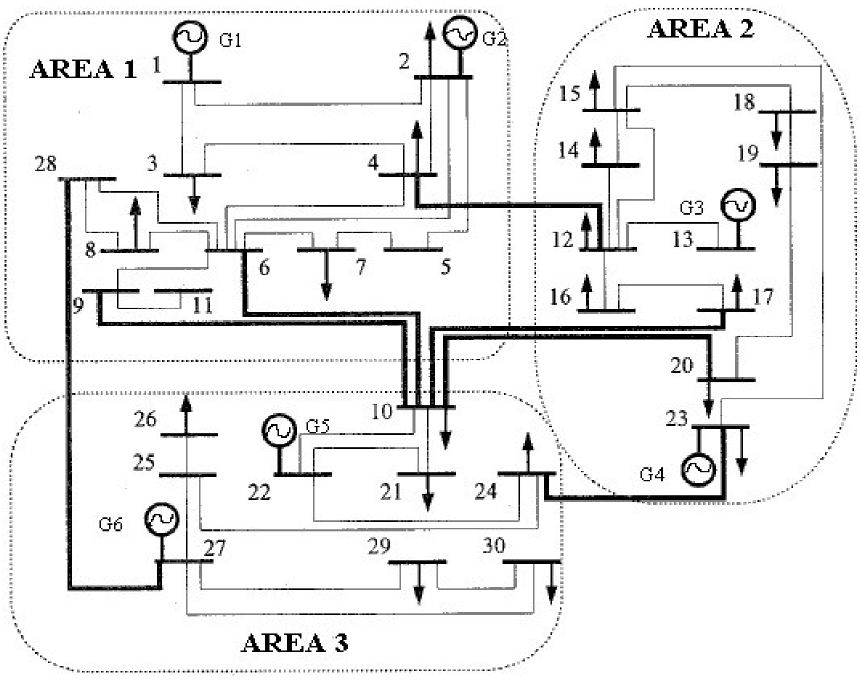


Figure 2.5 Modified IEEE 30 Bus Test System

Table 2.8 AREAS IN MODIFIED IEEE 30 BUS

Area	Bus	Gen Capacity (MW)	Load (MW)	Margin (MW)
1	1,2,3,4,5,6 7,8,9,11,28	121.94	84.5	37.44
2	12,13,14,15,16 17,18,19,20,23	40	76.2	-
3	10,21,22,24,25 26,27,29,30	105	48.5	56.5

Table 2.9 TIE LINES IN IEEE 30 BUS SYSTEM

Area	Tie Lines
1 to 2	4-12
1 to 3	9-10,6-10,28-27,
2 to 3	17-10,20-10,23-24

The proposed method is used to evaluate the ATC of the system. Taking CBM to be 15 MW, the ATC computed is found to be 63.525 MW, TTC is 78.515 MW, and available generation capacity in area 1 is 38.06 MW. The pattern search optimization takes five iterations with 526 function evaluations to reach the best function value of -0.7851496 Figure 2.6.

b) Transaction from area 3 to 2

The convergence characteristics of pattern search for transaction from area 3 to 2 given in Figure 2.8 is for the case where the slack bus is limited by its maximum generation limit. It can be seen that the TTC for this transaction using the proposed method is 76.3058, ATC is 61.306 (Taking CBM to be 15 MW).

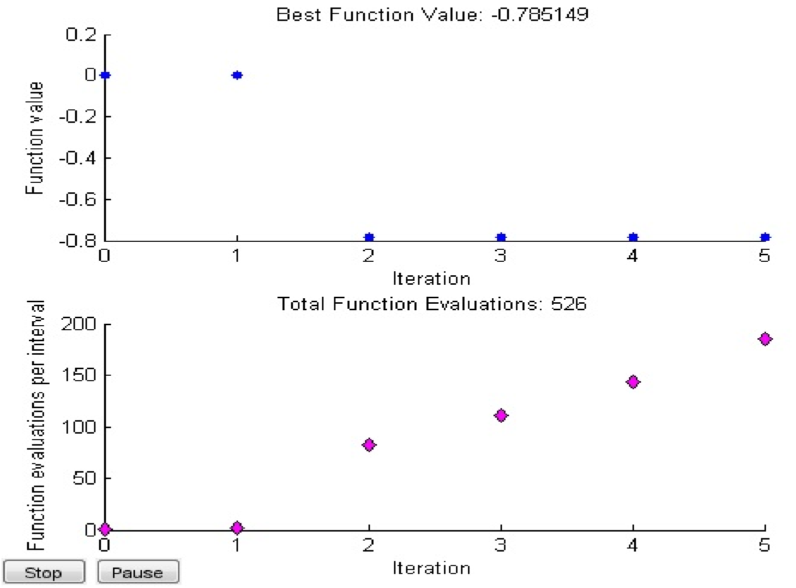


Figure 2.6 Convergence for transfer from area 1 to 2 with slack bus limited by Five times of P^{max}.

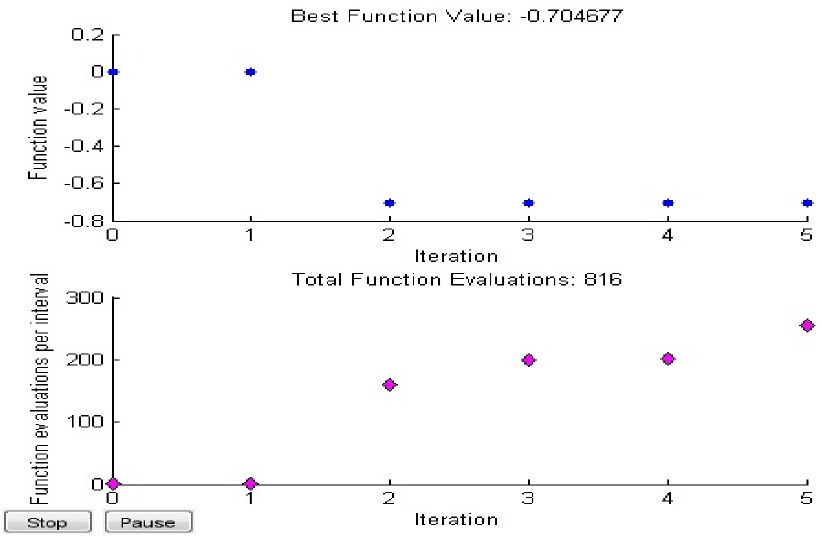


Figure 2.7 Convergence for transfer from area 1 to 2 with slack bus limited by P^{max}.

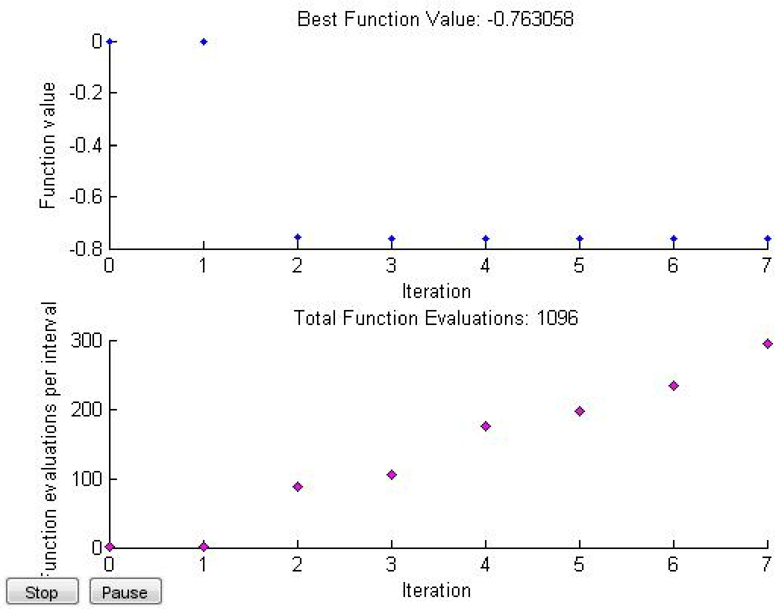


Figure 2.8Convergence for transfer from area 3 to 2 with slack bus limited by P^{max}.

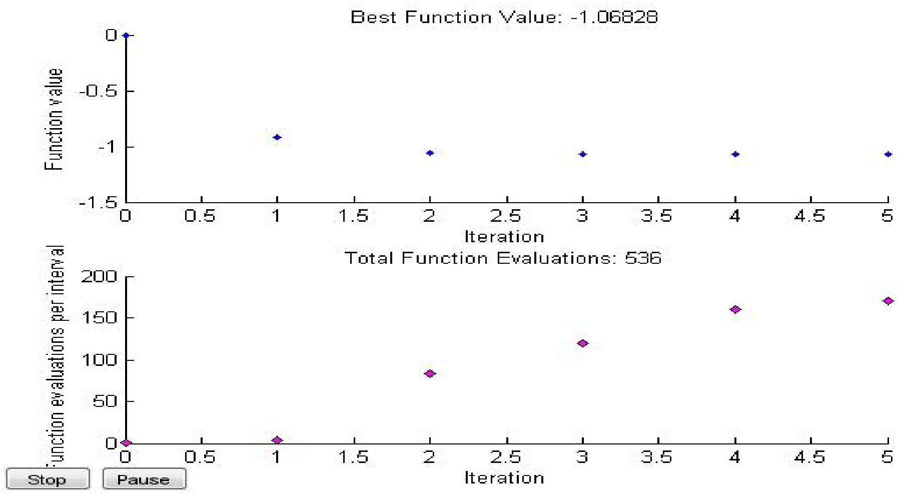


Figure 2.9 Convergence for transfer from area 3 to 2 with slack bus limited by Five times its P^{max}.

The pattern search takes seven iterations with the best function value of -.763058, and the available generation capacity in area 3 is 56.5 MW. In another case, the slack bus limit is made five times its maximum value, and then the TTC is obtained using the proposed method. The convergence plot is given in Figure 2.9; it can be seen that in this situation, pattern search optimization converges in 5 iterations, with the best function value being -1.06828 and ATC for the transaction being 91.828 MW. The number of function evaluations was 536, and the available generation capacity of area 3 is 56.5 MW. It can be inferred from the observations that the slack bus plays a pivotal role in determining the ATC for a different transaction. When the slack bus limit is altered, then the ATC value for all the transaction is altered. The distribution of incremental generation among the generators of the source bus also affects the ATC.

2.5 ENHANCEMENT OF AVAILABLE TRANSFER CAPABILITY

The ATC assessment problem formulated in the previous section could be modified for incorporating the ATC Enhancement aspect. The ATC at any particular instant for a given scenario depends on the existing power-flows through the transmission lines, and hence altering the power flow could affect the transfer capability of the network. Flexible AC Transmission System (FACTS) devices are capable of modulating the power flows through the line and thus could probably be utilized for enhancing the ATC of the system. In this section, a multi-stage approach for ATC assessment and enhancement would be discussed. The method involves two stages, in $Stage1$ Real-Time Contingency Analysis (RTCA) is performed for the input network information. The network information can be obtained from an amalgam of information provided by the Topology Processor (TP) and SCADA measurements for the system. RTCA provides a set of credible contingencies that are used in the next stage for obtaining the ATC. In $Stage2$, ATC assessment and enhancement engines are described, which utilizes pattern search optimization for obtaining the ATC. Further, the effect of FACTS devices has been employed for enhancing the ATC. The developed method is tested on a modified IEEE24 bus test system whereby the effect of renewable generation (Solar PV) has been inculcated.

2.5.1 Modeling of FACTS Devices

FACTS devices, namely SVC and TCSC, have been considered in this work. The modeling of these devices has been given in the following sections.

2.5.1.1 *TCSC Modelling*

Diagrammatic representation of TCSC has been shown in Figure 2.10. The equivalent reactance of TCSC can be represented as a function of its capacitive and inductive reactance along with the firing angle.

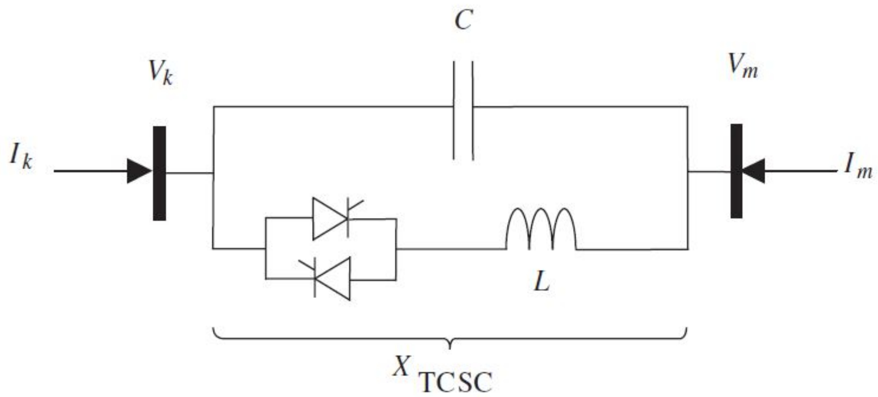


Figure 2.10 Schematic representation of TCSC modeling.

$$X_{TCSC} = -X_C + C_1[2(\pi - \alpha) + \sin(2\pi - \alpha)] + C_2 \cos^2(\pi - \alpha)\,[\omega \tan(\omega(\pi - \alpha)) - \tan(\pi - \alpha)] \quad 2.24$$

Where,

$$X_{LC} = \frac{X_C X_L}{X_C - X_L} \quad 2.25$$

$$C_1 = \frac{X_C + X_{LC}}{\pi} \quad 2.26$$

$$C_2 = \frac{4X_{LC}^2}{X_L \pi} \quad 2.27$$

The TCSC transfer admittance matrix between the nodes k and m is obtained as

$$\begin{bmatrix} I_k \\ I_m \end{bmatrix} = j \begin{bmatrix} B_{kk} & B_{km} \\ B_{mk} & B_{mm} \end{bmatrix} \begin{bmatrix} V_k \\ V_m \end{bmatrix} \qquad 2.28$$

Modified active and reactive power injections at bus k on account of TCSC are

$$P_k = V_k V_m sin(\theta_k - \theta_m) \qquad 2.29$$

$$Q_k = -V_k^2 B_{kk} - V_k V_m B_{km} cos(\theta_k - \theta_m) \qquad 2.30$$

The linearized power flow equations considering the TCSC model considered is obtained as

$$\begin{bmatrix} \Delta P_k \\ \Delta P_m \\ \Delta Q_k \\ \Delta Q_m \\ \Delta P_{km}^{X_{TCSC}} \end{bmatrix} = \left(\begin{bmatrix} \frac{\partial}{\partial \theta_k} \\ \frac{\partial}{\partial \theta_m} \\ \frac{\partial}{\partial V_k} \\ \frac{\partial}{\partial V_m} \\ \frac{\partial}{\partial X_{TCSC}} \end{bmatrix} \times \begin{bmatrix} P_k \\ P_m \\ \theta_k \\ \theta_m \\ P_{km}^{XTCSC} \end{bmatrix}^T \right)^T \qquad 2.31$$

In the above equation, $\Delta P_{km}^{X_{TCSC}} = P_{km}^{reg} - P_{km}^{X_{TCSC,cal}}$ represents the active power mismatch.

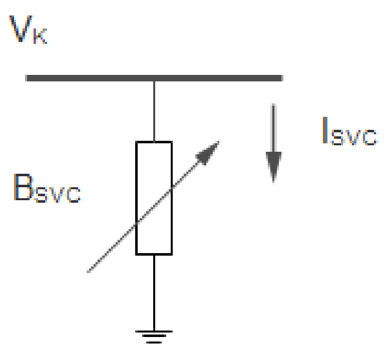


Figure 2.11 Diagrammatic illustration of SVC modeling.

2.5.1.2 *SVC Modelling*

Modeling of SVC has been materialized by representing the SVC characteristics with an adjustable reactance. An equivalent circuit representation of the model has been diagrammatically shown in Figure 2.11. The current, I_{SCV} drawn by the equivallent model of SVC is which is $jB_{SVC}V_k$ and $Q_{SVC} = Q_k = -V_k^2 B_{SVC}$ is the reactive injected. Taking B_{SVC} as state variable, the linearized power balance equation as given in (2.58) would be obtained.

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & Q_k \end{bmatrix} \begin{bmatrix} \Delta\theta_k \\ \dfrac{\Delta B_{SVC}}{B_{SVC}} \end{bmatrix} \quad 2.32$$

2.5.2 RENEWABLE SOURCE MODELLING: - MODELLING OF SOLAR PV

The Solar PV has been modeled as a PQ load where P will be negative for the generation (i.e., injection to the grid), and Q would be positive or negative depending upon the operating conditions of the SMART inverter through which the PV is connected. The output power P at any operating instant for the PV module is the product of model output voltage and output current, which are determined by the following equations as in [98]

$$I(V) = I_{SC}\left\{1 - C_1\left[exp\left(\frac{V + \Delta V}{C_2 V_{oc}}\right)\right]\right\} + \Delta I \quad 2.33$$

Where,

$$C_2 = \frac{\frac{V_{mp}}{V_{oc}} - 1}{\ln(1 - \frac{I_{mp}}{I_{sc}})} \quad 2.34$$

$$C_1 = \left(1 - I_{mp}/I_{sc}\right) \times \exp\left(-\frac{V_{mp}}{C_2} V_{oc}\right) \quad 2.35$$

$$\Delta I = \alpha \left(\frac{S}{S_{ref}}\right) \Delta T + \left(\frac{S}{S_{ref}} - 1\right) . I_{sc} \quad 2.36$$

$$\Delta V = -\beta \times \Delta T - R_s \Delta I \quad 2.37$$

$$\Delta T = T - T_{ref} \quad 2.38$$

$$T = T_A + 0.02S \quad 2.39$$

In the above equations, α is current change temperature coefficient at reference insolation (Amps/◦C); β is voltage change temperature coefficient at reference insolation (Volts/◦C); I, I_{mp} and I_{sc} are Module Current, Maximum Power Current and Short Circuit Current (Amps); S and S_{ref} stands for total insolation and reference insolation. R_s represents module series resistance. T, TA, and T_{ref} are cell, ambient and reference temperatures (◦C) while ΔT is change in cell temperature; V, V_{mp} and V_{oc} are module voltage, maximum power voltage, and open-circuit voltage (Volts). The beta distribution has been taken to realize the probability density function of solar irradiance of each hour has been obtained using the beta distribution of that hour. The active and reactive power support available from the SMART inverter [136], including inverter, is determined by the following equations: -

$$P^{inv} = P - P_{losses}^{inv} \quad 2.40$$

$$Q^{inv} \approx Q \quad 2.41$$

$$P_{losses}^{inv} = (1 - \eta_{inv}).\sqrt{P^2 + Q^2} \quad 2.42$$

The maximum value of $\left|Q_{max}^{inv}\right|$ is a function of real power generation and is determined by (2.58)

$$\left|Q_{max}^{inv}\right| = \sqrt{S^2 - P^2} \tag{2.43}$$

2.5.3 Problem Formulation: - ATC Determination and Enhancement

The basic ATC determination formulation has been inked in equation 2.1. Assessing the value of ATC translates to an optimization problem of equation 2.2. These formulations could be extended for simultaneous ATC determination and enhancement. Contingencies play a major role in determining the appropriate ATC value; the credible contingencies should be considered for assessing the ATC of the system. For real-time ATC assessment, real-time contingency analysis has to be done. The ATC assessment problem requires the information pertaining to the credible and most severe contingency to which the system may be subjected. A method for real-time contingency analysis for ATC has been formulated as $Stage1$ of ATC determination and enhancement.

2.5.3.1 *Stage1*

RTCA is a vital function of the modern energy management system. The RTCA is performed to identify the critical contingencies that would adversely affect the performance and reliability of the power system [137]. As optimization is not required for performing RTCA, the computing process does not enforce any constraints. In this work, an algorithm for RTCA is developed using $MATPOWER$ using equation (2.44) for contingency ranking as used in [70].

$$PI_c = \sum_i \left(\frac{d_{v,i}^u}{g_{v,i}^u}\right)^{2n} + \sum_i \left(\frac{d_{v,i}^l}{g_{v,i}^l}\right)^{2n} + \sum_i \left(\frac{d_{p,i}}{g_{p,i}}\right)^{2n} \tag{2.44}$$

Here,

$$d_{v,i}^{u} = \begin{cases} \dfrac{V_i - F_i^u}{V_i^d} & ; \quad if \quad V_i > F_i^u \\ 0 & ; \quad if \quad V_i \leq F_i^l; \end{cases} \qquad 2.45$$

$$d_{v,i}^{l} = \begin{cases} \dfrac{F_i^l - V_i^u}{V_i^d} & ; \quad if \quad V_i > F_i^l \\ 0 & ; \quad if \quad V_i \leq F_i^u; \end{cases} \qquad 2.46$$

$$g_{u,i}^{v} = \frac{[V_i^u - F_i^u]}{V_i^d} \qquad 2.47$$

$$g_{u,i}^{l} = \frac{[F_i^l - V_i^l]}{V_i^d} \qquad 2.48$$

$$d_j^p = \begin{cases} \dfrac{[|P_j| - P_j^F]}{BaseMVA} & ; \quad if \quad |P_j| > P_j^F \\ 0 & ; \quad if \quad P_j \leq P_j^F \end{cases} \qquad 2.49$$

$$g_{p,j} = \frac{[P_j^P - P_j^F]}{BaseMVA} \qquad 2.50$$

In the above equations PI_c is the contingency index, V^i is the voltage of i^{th} bus, V_i^d is the desired voltage at each node, $F_i^u, F_i^l, V_i^u, V_i^l$ represent the alarm limits and the security limits with $d_{v,i}^u, d_{v,i}^l, g_{v,i}^u, g_{v,i}^l$ stands for their normalized upper and lower limit violation. Similarly, for line flows, the normalized power flow limit violations are $d_{p,i}, and\ g_{p,i}$ means the normalization factor. The n is exponent used in hyper ellipse equation [70] and is taken as 2. The composite security index (2.44) is used for obtaining the contingency ranking. The contingency that has the highest index is the most severe, and the one with the smallest value of the index is the least severe.

2.5.3.2 *Stage 2*

The ATC of a system primarily depends on the health of the network (contingency status), active & reactive flows in the network, along with the loading and generation scenario of the grid. Therefore, all the parameters $(Pd;\ c;\ B_{SVC};\ X_{TCSC})$ would be taken as arguments of the objective function. Now, the power generated from the renewable source would be varying with time. Determination of power generated from such sources at any time has been explained in section 2.5.2. For any specific time, the output power of generators would be fixed. The power flows through the network can be modified by the variation in settings of FACTS devices as given in equations (2.31) and (2.32). Maximum ATC value would be obtained for optimal B_{SVC} and X_{TCSC} therefore they would be used as input arguments and control parameters of objective function.

For ATC evaluation when FACTS devices are not taken into consideration, the ATC would be evaluated using equation (2.2) as given hereunder: -

$$Max(f)$$
$$\text{where, } f = \sum_{i=1}^{N}(Pd_i - Pd0_i) \qquad 2.51$$

If FACTS devices are present in the network, the power flow would be modified. However, their control parameters have to be optimized for maximizing the ATC for which the modified equations could be written as

$$Max(f(Pd, B_{SVC}, X_{TCSC})$$
$$f(\cdot) = \sum_{i=1}^{N}(Pd_i - Pd0_i) \qquad 2.52$$

The above formulation would be valid if RTCA is not desired during the computation. In case RTCA is desired, a set of credible contingencies would be obtained, and the optimal ATC value would be the minimum of all the ATC values obtained corresponding to the set of credible contingencies. Thus, with the above consideration, the equation (2.58) would be rewritten as

$$Min(Max\, f(Pd, c, B_{SVC}, X_{TCSC}) \qquad 2.53$$

$$f(\cdot) = \{f_{c1}, f_{c2} \cdots f_{ck}\} \rightarrow k\ is\ number\ of\ critical\ contingencies \qquad 2.54$$

$$f_{ck}(Pd, B_{SVC}, X_{TCSC}) = \sum_{i=1}^{N} (Pd_i - Pd0_i) \qquad 2.55$$

The objectives described in equation (2.53) would be solved by adhering to the impediments laid in equations (2.4-2.9) while satisfying the following additional constraints.

$$c_k \subseteq C\ ; C\ is\ set\ of\ credible\ contingencies \qquad 2.56$$

$$B_{SVC}^{l} \leq B_{SVC} \leq B_{SVC}^{U};\ B_{SVC}^{l} \text{ and } B_{SVC}^{u} \text{are limiting values of SVC} \qquad 2.57$$

$$X_{TCSC}^{l} \leq X_{TCSC} \leq X_{TCSC}^{u};\ X_{TCSC}^{l} \text{ and } X_{TCSC}^{u} \text{ are limiting values of SVC} \qquad 2.58$$

The MinMax optimization given in (2.53) strives to maximize the ATC corresponding to each credible contingency available in the set of credible contingencies provided by the RTCA and at the same time yields the minimum value of ATC. This is done because the ATC corresponding to the contingency, which would yield the minimum value of ATC, would be considered as the final value. If the system is scheduled considering minimum ATC and any other credible contingency happens then, the system would be able to operate reliably and securely. Contrarily, if a higher value of ATC is scheduled and the contingency corresponding to a minimum value of ATC happens, then the system won't be able to satisfy its operational commitments.

2.5.4 Solution Methodology

The schematic of the solution for the problem of ATC assessment and enhancement is illustrated in Figure 2.12, and the overall process has been given as a flowchart in Figure 2.13.

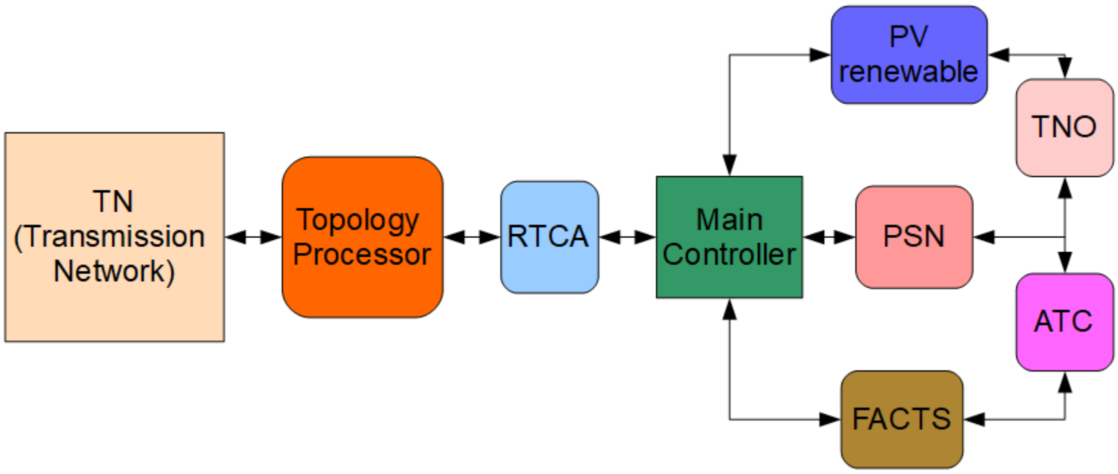


Figure 2.12 Schematic representation of a proposed method for ATC assessment and enhancement.

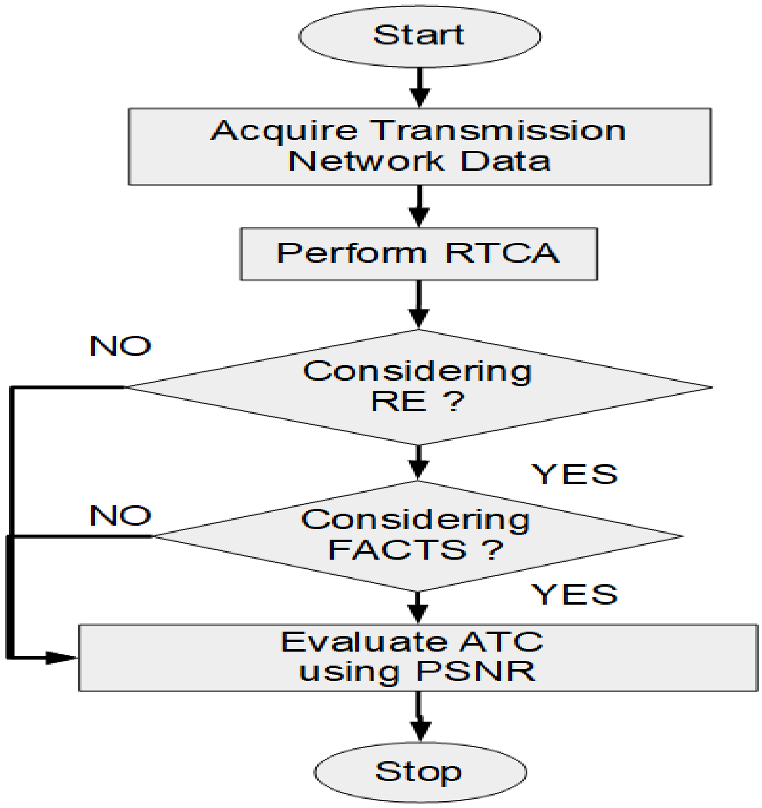


Figure 2.13 Flowchart showing the various steps of the solution process.

The function of the different blocks is explained as under:

2.5.4.1 *TN (Transmission Network):*

The test system under study is designated as the TN (Transmission Network) and fed as input to the topology processor. TN contains the information regarding the transmission lines, transformers, FACTS devices, generators, loads, and areas in the considered system.

2.5.4.2 *Topology Processor:*

The topology processor processes the TN data to obtain information like the number of areas in the system, identifying tie lines between them, total load in each area, total generation in each area, available generation capacity (AGC) in each area. It forms the admittance matrix depending upon the status of the transmission lines and transformers in the system.

2.5.4.3 *RTCA:*

RTCA developed in II-A has been used to determine the set of credible contingencies (CC). It employs the PSN solver (PSN) block for obtaining the PI_c. The set CC contains the contingency in the decreasing order of their severity. Therefore, the first item is the sever most contingency as far as static security is concerned [70].

2.5.4.4 *Main Controller:*

Main Controller interacts with the different components for channelizing the process of ATC assessment and enhancement. Main Controller contains the subroutine, which enables it to communicate the information to and from the components such as PV element, FACTS devices, PSN, TNO, and ATC.

2.5.4.5 *PV Renewable and FACTS:*

This block contains the PV and Smart inverter module and communicates with the main controller to know its status, location, and mode of operation. The PV, when connected to the grid through smart inverters, can provide reactive power depending upon their rating. FACTS block contains the models of the TCSC and the SVC, and they communicate with the main controller to know about the number of devices, their location in the system, and their ratings.

2.5.4.6 *PSN, TNO, and ATC engine:*

PSN block contains different network solver subroutines such as Newton Raphson, Fast Decupled Load Flow, DC power flow, Optimal Power Flow, and Continuation Power Flow. It communicates with the main controller block, TNO (Transmission Network Optimizer) block, and obtains the solution of the network using the solver asked by the master (communicating block). Transmission Network Optimizer communicates with the main controller, FACTS block, to achieve optimal settings of control variables of FACTS devices. TNO also communicates with the ATC engine, which contains subroutines of optimization technique which is used for solving the problem formulated in (2.53).

The ATC engine uses Pattern search optimization proposed in [138] for ATC assessment and enhancement. It is a direct search optimization where the information regarding the gradient of the objective function is not required. The direct search algorithm searches a set of points around the current point, looking for the optimum point of the problem.

2.5.5 Case Study

The developed method operational strategy is tested on a modified IEEE 24 bus RTS test system. The data for the system has been taken from [138]. The description of the test system is given as under.

2.5.5.1 *Description of the test System*

The considered IEEE 24 bus test system is divided into three areas AREA1 (A1), AREA2 (A2), and AREA3 (A3), as shown in Figure 2.14. The information of different areas is given in Table 2.1, tie lines in Table 2.2, and modifications in generation capacity (Conventional generation) in Table 2.3. In addition to the above modifications, an SVC is placed at bus 24. and TCSC is placed in L19, which is a line connecting the Bus11 and Bus14.

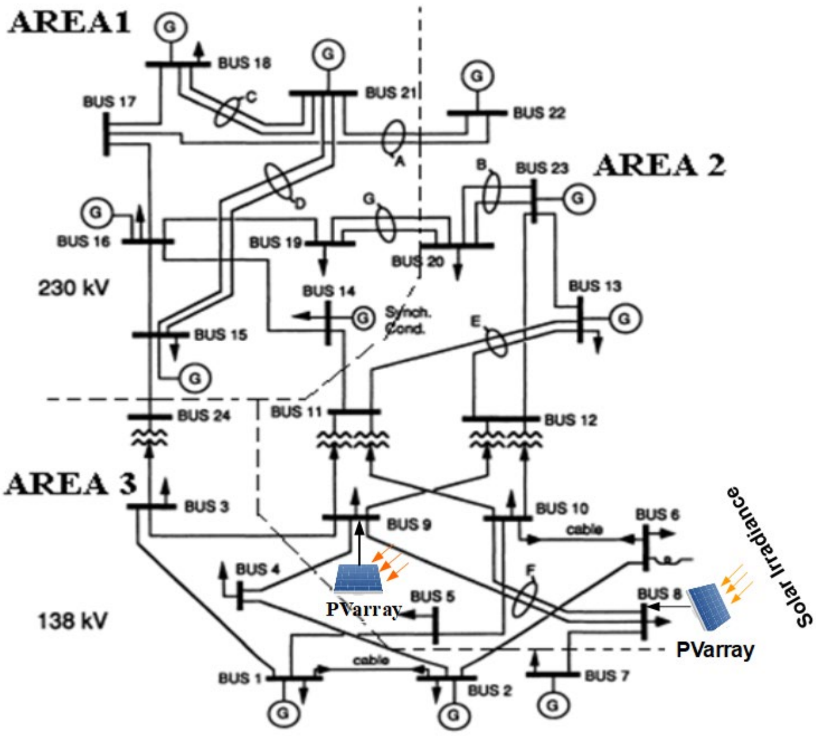


Figure 2.14 Modified IEEE 24 BUS RTS test system.

Table 2.10 PV panel parameters

Parameter	Value	Parameter	Value
α	00.12	S_{ref}	1000
V_{oc}	64.60	I_0	2.96E-10
β	07.35	R_s	0.39383
T_A	25.00	R_{sh}	313.3992
I_{mp}	07.84	V_{mp}	54.7
I_l	07.81		

Table 2.11 SET of Credible Contingencies

Se. No.	Line No	From Bus	To Bus	PI
1	7	3	24	0.640363
2	29	16	19	0.052613
3	22	13	23	0.050668
4	28	16	17	0.024653

The SVC is capable of providing -40/60 MVar compensation, and TCSC is can provide 30% compensation to the line to which it is connected. PV system of 10 MW is connected at Bus9 in area 2. The PV system comprises 275 modules of PV arrays (each module consisting of 52 PV panels), 5 connected in series and 55 in parallel. The parameters of the PV panel used in this work are given in Table 2.10**.** The $I - V$ characteristic of the solar panel for a different combination of S and T_A is given in Figure 2.15.

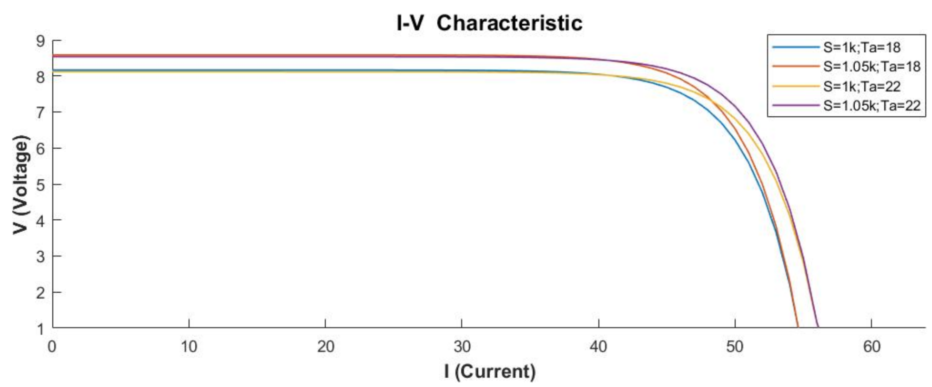


Figure 2.15 I-V characteristic of considered solar panels for different S and TA

Table 2.12 ATC for Transaction from A1 to A2.

S No	SVC	TCSC	PV	RTCA	TTC	CBM	ATC
1	0	0	0	0	352.904	57.05	295.854
2	1	0	0	0	354.82	57.05	297.77
3	0	1	0	0	424.77	57.05	367.72
4	1	1	0	0	424.77	57.05	367.72
5	0	0	1	0	354.041	56.5908	297.45
6	1	0	1	0	352.12	56.5908	295.53
7	0	1	1	0	426.381	56.5908	369.79
8	1	1	1	0	426.381	56.5908	369.79
9	0	0	0	1	245.114	57.05	188.064
10	1	0	0	1	252.428	57.05	195.378
11	0	1	0	1	244.647	57.05	198.597
12	1	1	0	1	244.588	57.05	198.538
13	0	0	1	1	247.089	56.5908	190.498
14	1	0	1	1	254.382	56.5908	197.791
15	0	1	1	1	272.573	56.5908	215.982
16	1	1	1	1	272.573	56.5908	215.982

2.5.5.2 *Result and Discussion*

The method proposed in this chapter is used to assess and enhance the ATC of the test system described above. RTCA is employed to obtain the set of credible contingencies for the system and the CC along with their PI_c are given in Table 2.11. The ATC for transactions from area 1 (A1) to area 2 (A2) is evaluated. Pattern search optimization discussed in section 2.4.3 is used whereby loads in the sink area (A2) are increased, and equivalent increment of generation is done in source area 1 (A1) so that the GLBM (Generation Load Balance Matching) is attained. The results of ATC enhancement while considering the various combinations of operations have been tabulated in Table 2.12. The table shows device/RTCA status as 0 or 1 in the first four columns. Status 0 indicates that the device/RTCA has not been considered in evaluating the ATC, whereas status 1 is considered. For example, the ATC corresponding to row R1 is evaluated without considering any of the components, while in row 16, all the components are considered. It can be seen from the table that the ATC in R1 < R2 < R3 this implies that the ATC without considering any FACTS device is lesser than that obtained while considering the FACTS device. Further, the impact of TCSC in enhancing the ATC is much greater than that of SVC as R2 < R3, R10 < R11, and R14 < R15. The presence of PV (the solar insulation is considered as 1.2 p.u day time) also affects the ATC value. The ATC increases due to consideration of the PV system, as can be seen from R5 > R1, R13 > R9. It can also be inferred from the results that if both the TCSC and ATC are present in the system, then the final value of ATC is controlled by the TCSC R3 = R4, R11 = R12, and R15 = R16.

2.6 CONCLUSION

In this chapter, a pattern search-based optimization technique has been proposed for ATC estimation. The proposed technique has been used for the analysis of the IEEE 24 bus RTS system and IEEE 30 bus test system. In the analysis, an emphasis has been laid on identifying the significance of slack bus for ATC evaluation. The methodology presented in this chapter can be utilized for the offline evaluation of ATC. The technique can be used to obtain ATC data for existing loading patterns. This data can be used for the training of neural networks for online applications.

In addition, the optimal strategy for ATC assessment and enhancement has also been proposed, along with the technique for consideration of the set of credible contingencies obtained from RTCA using an ATC optimization engine. The developed ATC optimization engine uses pattern search optimization for obtaining the solution of ATC. The propounded method has been employed for assessing the impacts of TCSC and SVC on the ATC enhancement. It has been observed that the presence of a PV system could significantly affect the ATC value. In the next chapter, the methodology of the PPMU emulator required for developing a real-time ATC estimator would be discussed.