RECENT AVAILABLE TRANSFER CAPABILITY CALCULATION METHODS: A REVIEW

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ABSTRACT

This paper reviews on the features and implementation of various methods, with pros and cons, for available transfer capability (ATC) calculations. ATC indicates remaining transfer capability over and above already committed use in a competitive electricity market for its commercial use. Over calculated ATC will offer more power transactions, which will decreases system's security. On the other hand, under calculated ATC will offer lesser transactions which will affect market economy. To operate the competitive electricity market securely while earning the benefits of bulk power transfers, the available transfer capabilities must be calculated in advance to keep market operation within pre-established reliability level. The methods reviewed are based on DC Power Transfer Distribution Factors (DCPTDF), repeated AC Power Flow, genetic algorithm and artificial neural network.

KEYWORDS—*Available Transfer Capability (ATC), Artificial Neural Network (ANN), Continuation Power Flow (CPF), DC Power Transfer Distribution Factors (DCPTDF) method, Genetic Algorithm (GA), Repeated AC Power Flow (PRF).*

I. INTRODUCTION

ATC calculation has been a research area of exponentially increasing interest, due to economic and reliability consideration, particularly in the past two decades. The aspire at the back of restructuring electricity market is to bring some form of competition among the market participants, open access to all, to provide options and benefits to the end user customers. In order to bring the competitiveness and to maintain reliability in electricity industries, the transmission network capability and generation capacity of the power system should be made available, at a regular small interval, to the market participants well in advance by independent system operator (ISO) before bid, to enable the market participants to use the existing transmission system efficiently.

The U.S. Federal Energy Regulatory Commission (FERC) issued orders 888 and 889, which established open access non-discriminatory transmission services policy and Open Access Same-time Information System (OASIS). ATC is required to be posted on publicly accessible web at a small regular interval well in advance before bid. This necessitates the calculation of ATC of transmission path [1] in deregulated electricity market. Over calculated ATC will offer more power transactions, which will decrease system's security. Under calculated ATC will offer lesser transactions, affecting market economy. To avoid the undesirable impacts of open access in an energy market such as heavier line loadings and increased loop flows, a clear indication of system ATC is required [2]. North American Electric Reliability Council (NERC) defines ATC as a "measure of transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses [2].

Mathematically, ATC is defined as the Total Transfer Capability (TTC) less the Transmission Reliability Margin (TRM), less the sum of Existing Transmission Commitment (ETC) (which includes retail customer service) and the Capacity Benefit Margin (CBM). ATC can be expressed as:

$$ATC = TTC - TRM - ETC - CBM \quad (1)$$

NERC defines TTC between any two areas or across particular path or interface as an "amount of electric power that can be transferred over the interconnected transmission network in a reliable manner without violation of thermal limits, voltage limits and dynamic stability limits". TTC is direction specific and consistent with the First Contingency Total Transfer Capability (FCTTC) as defined by NERC's May 1995 Transmission Transfer Capability reference document [3].

Deterministic methods and mathematical methods are based on power flow solutions such as RPF [4, 5], continuation power flow method (CPF) [4, 6, 7], optimum power flow (OPF) method [8], and sensitivity based methods [10-26]. Probabilistic methods for determining ATC serve as offline optimization tool and are generally used during planning stage [30-32]. Literature reveals that ANN-based ATC estimators are also suitable due to high speed, accuracy, generalization and ability to deal with noisy data reported in [37-42].

This paper is organized as follows: Section 2, 3, 4 and 5 presents the review on ATC calculation methods of repeated AC power flow, DC power transfer distribution factors, genetic algorithm and artificial neural network with concept and implementation. Section 6 concludes the reviews.

II. ATC CALCULATION USING REPEATED POWER FLOW APPROACH

In [4], G. C. Ejebe et al. reported a novel formulation of the ATC problem based on full AC power flow solution to incorporate the effects of reactive power flows, voltage limits, voltage collapse and thermal loading effects. An efficient continuation power flow approach with adaptive localization enhances speed in processing a large number of contingencies to determine ATC for each specified transfer. The CPF algorithm effectively increases the controlling parameter in discrete steps and solves the resulting power flow problem at each step. The procedure is continued until a given condition or physical limit preventing further increase is reached. Proposed method use Newton power flow algorithm and requires Jacobean matrix calculation once in iteration. Hence, speed of proposed method is very slow.

RPF method implementation for ATC calculation is simple, and also suitable for large-scale power systems. In RPF method, the system load and power generation will be increased by a specified rate and continues until one of the system operating limits related to ATC is violated.

Steps for ATC calculation using RPF for a selected transaction path are as follow:

1. Solve the base case power flow for a particular instant.
2. Identify suitable step increase in transfer power.
3. Set up new base case power flow problem consisting of the original base case modified by the increases in transfer power and solve power flow problem.
4. Check violations of system operating limits of solution of step 3. If there are violations; decrease the step increase to eliminate them.
5. Solve the power flow problem of steps 1 - 4 for each listed contingency. If there are violations, decrease the step increase to eliminate them. This is the ATC for the case.
6. Return to step 1 for the new transaction case.

The polar power flow equations are:

$$P_i = \sum_{j \in i} V_i V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}\right) \quad (2)$$

$$Q_i = \sum_{j \in i} V_i V_j \left(G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}\right) \quad (3)$$

For ATC calculation, variations in the real power generation and demand for each bus are functions of λ.

$$P_{Gi} = P_{Gi}^{0}(1+\lambda K_{Gi}) \quad (4)$$

$$P_{Dj} = P_{Dj}^{0}(1+\lambda K_{Dj}) \quad (5)$$

Where P_{Gi} and P_{Dj} are the real power injection and extraction at bus i and j, P_{Gi}^0 is the original real power generation at bus I, P_{Dj}^0 is the original real load demand at bus j, λ is the scalar parameter and K_{Gi} and K_{Dj} are the participation factors.

TTC can then be calculated using the Eq. (6). The TTC calculation is based on static consideration and considers voltage limits and thermal limits in the calculation. The equation shows the TTC of an electric power system before reaching the voltage collapse point along with the maximum permissible exchange flows on interfaces, which have not violated the capacity limitation.

$$TTC = min\ [(\Sigma_{j\in k} P_{Dj}(\lambda_{max}) - \Sigma_{j\in k} P_{Dj}(\lambda_0)), \Sigma_{ij\in Tie\ Lines} P_{max-ij}] \quad (6)$$

Where, $\Sigma_{j\in k} P_{Dj}(\lambda_{max})$ is the sum of the load in sink area at $\lambda=\lambda_{max}$, $P_{Dj}(\lambda_0)$ is the sum of the load in sink area when $\lambda=0$, and $\Sigma_{ij\in Tie\ Lines} P_{max-ij}$ is the sum of tie lines capacity between the sending and the receiving area.

The ETC is calculated using the power flow calculation. The TRM can be treated as a constant percentage of the TTC. The CBM can be based on the market value. For the sake of simplicity, TRM and CBM are assumed to be zero. Based on the above assumptions, ATC can be estimated by (1). RPF is the accurate method but require an extraordinary amount of computation time for most of real systems and for this reason, not suitable for real time application.

III. SENSITIVITY BASED APPROACH

For nearly all real power systems, ATC calculation using CPF, OPF and RPF methods would require an extraordinary amount of computation time and for this reason, simplified methods, even if they have less accuracy, needed to be used. Power flow sensitivity based methods are fast methods for ATC determination and also well proven. Many authors have proposed power flow sensitivity based methods for fast determination of ATC. This method is based on power transfer distribution factors (PTDFs) or line outage distribution factors (LODFs) using DC load flow approach. These factors can be derived in many ways and basically come down to above two types [10]. ATC calculation based on power transfer distribution factors (PTDFs) and line outage distribution factors (LODFs) using DC load flow approach reported in [11].

In [12], G. Hamoud proposed method of ATC assessment using Probabilistic Composite System Evaluation program (PROCOSE). This program provides a good tool for computing the ATC of a transmission system and identifying the most limiting facilities affecting the ATC. PROCOSE uses a dc power flow model to simulate the operation of the power system, taking into account outages of generating units, economic dispatch, fixed power injections, system load profile, transmission outages and limits imposed on the transmission network. In [13], Comprehensive approach for ATC determination in multi-transactions environment using DCPTDF based problem formulation is reported. DC load flow method has a poor accuracy when X/R ratio is low due to assumptions of DC load flow [14]. This method is very useful due to its simplicity in calculation and speedy outcomes, hence a potential method for real time application. Many authors have proposed more accurate, than DC PTDF, power flow sensitivity methods based on AC load flow approaches [15–26]. Ashwani Kumar, S.C. Srivastava and S.N. Singh presented an application of bifurcation criteria for ATC calculation in a competitive power market having bilateral as well as multilateral transactions in [23]. In [24], an approach for power transfer distribution factors based calculation of TCSC reactance for ATC enhancement is presented. In [25], authors proposed a method of ATC determination in multi-transactions environment using AC power transfer distribution factors.

Sensitivity methods based on AC load flow approach are accurate compared to sensitivity methods based on DC load flow approach. On the other hand, sensitivity methods based on DC load flow approach are faster and suitable for real time applications if X/R ratio is more than 4 [14].

A. ATC Calculation Using DCPTDF

$DCPTDF_{ij-mn}$ is the sensitivity of power flow in transmission line ij to one unit increase in power transfer from source bus m to sink bus n with no outages in the network using DC power flow approach. The set of PTDF's for each power transfer is computed as follows:

$$DCPTDF_{ij-mn} = (X_{im} - X_{jm} - X_{in} - X_{jn}) / X_{ij} \quad (7)$$

$$P_{ij}^{mn} = P_{ij}^{0} + DCPTDF_{ij-mn} * P_{mn}^{tr} \quad (8)$$

Where, X_{ij} is reactance of line connecting bus i and bus j, X_{im} is i[th] row and m[th] column parameter of bus reactance matrix X, P_{mn}^{tr} is the real power transaction between bus m and bus n, P_{ij}^{0} is the real power flow between bus i and bus j before transaction between bus m and bus n and P_{ij}^{mn}.

For multi-transaction case, superposition principle is used to calculate power transfer as the calculation of DCPTDF is done using linearity property of DC load flow approach. For ATC, calculate the maximum possible power transfer, T_{ij-mn}, for all transmission lines ij are calculated as,

$$T_{ij-mn} = \begin{cases} (P_{ij}^{max} - P_{ij}^{0}) / DCPTDF_{ij-mn} & ; \text{for } DCPTDF_{ij-mn} > 0 \\ Infinite & ; \text{for } DCPTDF_{ij-mn} = 0 \\ (-P_{ij}^{max} - P_{ij}^{0}) / DCPTDF_{ij-mn} & ; \text{for } DCPTDF_{ij-mn} > 0 \end{cases} \quad (9)$$

ATC is limited by the permissible maximum power flow, P_{ij}^{max}, of any one transmission facility of the system.

$$ATC_{mn} = min\{T_{ij-mn}\}, \text{ where, line ij} \in \text{all transmission lines}$$

B. ATC Calculation Using DCLODF

The line outage distribution factors are used in a similar manner as PTDF. DCLODF, L_{ij-xz} is the sensitivity of power flow in transmission line i-j to the outage of line bus x to bus z carrying original power, before outage, P_{xz} in the network using DC power flow approach. The set of LODF's for each line outage is computed as follows:

$$DCLODF_{ij-xz} = \Delta f_{ij} / f_{xz}^{0} \quad (10)$$

$$f_{ij}^{xz} = f_{ij}^{0} + DCLODF_{ij-xz} * f_{xz}^{0} \quad (11)$$

Where, Δf_{ij} is change in real power flow on line ij after an outage on line xz, $DCLODF_{ij-mn}$ is the LODF when monitoring line ij after an outage on line xz, f_{xz}^{0} is original flow on line xz before it was outaged, f_{ij}^{0} is the original flow on line ij before line xz outage and f_{ij}^{xz} is the real power flow between bus i and bus j after outage of line xz.

DC outaged transfer distribution factor (OTDF) is calculated as follow:

$$OTDF_{ij-xz} = DCPTDF_{ij-mn} + DCLODF_{ij-xz} * DCPTDF_{xz-mn} \quad (12)$$

For ATC calculation considering line contingency, the maximum possible power transfer, T_{ij-mn}, for all transmission lines i-j are calculated as,

$$T_{ij-xz} = \begin{cases} (P_{ij}^{max} - f_{ij}^{xz}) / OTDF_{ij-xz} & ; \text{for } OTDF_{ij-xz} > 0 \\ Infinite & ; \text{for } OTDF_{ij-xz} = 0 \\ (-P_{ij}^{max} - f_{ij}^{xz}) / OTDF_{ij-xz} & ; \text{for } OTDF_{ij-xz} > 0 \end{cases} \quad (13)$$

ATC is limited by the permissible maximum power flow, P_{ij}^{max}, of any one transmission facility of the system given by,

$$ATC_{xz} = min\{T_{ij-mn}, T_{ij-xz}\}, \text{ where line ij and line xz} \in \text{all transmission lines}$$

IV. ATC CALCULATION USING GENETIC ALGORITHM

Heuristic methods such as GA, Particle swarm optimization for determining ATC are normally proposed during planning stage and serves as offline tool. Genetic algorithms are random search techniques and have broadly been applied in power systems as an optimization tools. Working principle is borrowed from natural genetics i.e. Darwin's principle of reproduction and survival of the fittest [27-30].

Basic steps involved in GAs are coding, fitness Function, constraints and convergence. Set of random population is generated, which all represents solutions. Fitness Function is a problem specific and represents single numerical fitness hence a measure of success. GA Operators choose better individuals and remove worst individuals by using GAs operator such as reproduction, crossover and mutation. Generated solution fitness is checked using fitness function. GAs may be considered as a multidimensional optimization technique based on a genetically random search.
In [31], Mozafari B. et al propose a genetic algorithm based method for computing ATC between two specific areas in the transmission network. Problem formulation is based on an OPF model considering AC power flow equations as equality constraints and active power generation costs of generators to dispatch them economically in every operating points of the system. Objective function tries to maximize total generation in sending area and consumptions in receiving area and simultaneously tries to minimize the cost of generation as well. In [32], K. Selvi et al proposed genetic algorithm based problem formulation to estimate TTC. In this paper, main objective function is maximized without system constraint violations and estimates the TTC between the two specific areas through global optimal search.

A. Problem Formulation

RPF method implementation for ATC calculation is simple, and also suitable for large-scale power systems. In RPF method, the system load and power generation will be increased by a specified rate and continues until one of the system operating limits related to ATC is violated. A problem of ATC calculation using GA can be formulated by using a simple implementation of RPF method, as discussed in section 2, as follows:

Maximize: λ, Subjected to:

$$P_i - \sum_{j\in i} V_i V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) = 0 \tag{14}$$

$$Q_i = \sum_{j\in i} V_i V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) = 0 \tag{15}$$

$$P_i = P_{Gi} - P_{Di} \quad and \quad Qi = Q_{Gi} - Q_{Di} \tag{16}$$

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \tag{17}$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \tag{18}$$

$$/V_i/^{min} \leq /V_i/ \leq /V_i/^{max} \tag{19}$$

$$P_{ij} \leq P_{ij}^{max} \quad and \quad P_{ji} \leq P_{ji}^{max} \tag{20}$$

Where, λ is a scalar which represents increase in load in receiving area i.e. Available transfer capability (ATC) in MW, P_{Gi} is the real power generation at bus i in MW, Q_{Gi} is the reactive power generation at bus i in MVAR, P_{Di} is the real power demand at bus i in MW, Q_{Di} is the reactive power demand at bus i in MVAR, $|V_i|$ is the voltage magnitude at bus i, P_{ij} is the real power transfer from bus i to bus j and P_{ij}^{max} is the maximum permissible real power transfer from bus i to bus j.

V. ATC CALCULATION USING ANN

Over the last decade, ANN has received much attention in the power system research community. The reasons for such a resurgence of interests in ANN are parallel computing structure and learning and generalization capability. ANNs mimic the neural brain structure of humans. ANN structure consists of simple artificial neurons units connected in layer architecture. ANNs are capable of representing any degree of nonlinear functions with suitable selection of numbers of hidden layers and neurons in a hidden layer. ANN learns these complex functions through sets of inputs and targets data using training algorithm [33-35]. The multi-layer feed-forward neural network [36], also known as the multi-layer perceptron (MLP) network, was developed in the early 1970's and is the most popular topology in use today.
Fast ATC calculating algorithms are usually approximate in some ways due to several assumptions and simplifications. Accurate methods are found to be computationally intensive and time consuming.

On the other hand artificial neural network (ANN)-based ATC estimation is quite accurate and almost instantaneous. In recent years, ANN-based approaches are found suitable for estimating ATC in spot power market scenario due to their robustness, speed and ability to deal with incomplete or noisy data [37–42]. These methods allow a system operator to immediately update ATC information as loads and the status of generation and transmission lines change.

In [39], authors have proposed a real power transfer capability calculations using multi-layer feed forward neural network for computing ATC between two specific areas in the transmission network. In this paper, MLP topology based solution methodology is presented. Problem formulation is based on Optimum power flow methodology. In [40], a Levenberg-Marquardt algorithm-based neural network method to determine ATC in a competitive electricity market without considering transmission reliability margins (TRM) has been proposed. In [41], authors have proposed a Levenberg-Marquardt algorithm neural network based approach for fast and accurate estimation of system ATC (SATC) using input variables selection by principle component analysis (PCA). The system ATC has been estimated for both varying load condition as well as for single line outage condition by employing distributed computing. Contingency clusters are formed such that each cluster contains almost similar ATC values. The proposed approach has been examined on 75-bus Indian power system and IEEE 300-bus system and found significantly efficient. In [42], a radial basis function neural network based method has been proposed to determine ATC in electricity markets, having bilateral as well as multilateral transactions. The number of hidden units, unit's centre and their widths, of the RBFNN has been determined using a Euclidean distance based clustering technique.

A. Basic Steps Involved in MLP Topology

1. Formulation/getting of Inputs and Targets set.
2. Selection of proper ANN topology.
3. Selection of Training and Testing set randomly.
4. Selection of training algorithm.
5. Selection of Stopping Criterion.
6. Training, testing and validation of ANN.

A problem of ATC calculation can be formulated by using an RPF solution methodology as stated in section 2.

B. Implementation of Algorithm

Available transfer capability (ATC) is a complex nonlinear function. It depends on load demand, configuration of system and generation. A neural network methodology to solve ATC problem is presented in this section.

C. Selection of Input Variables

For a given base case, generation level, load level and line status, define a power system state. Therefore the input variables selected are:

1. Generation level at a bus.
2. Line status
    a. 1 – Represents line status as available.
    b. 0 – Represents line status as unavailable.
3. Load level at a bus.

D. Network Architecture and Training

Multi-layer feed forward neural network is used as network. There is no general rule for selection of neural network architecture. Selection of neural architecture depends on complexity of a problem. For a more complex problem select, more numbers of neurons in neural network and less numbers of neurons for lesser complex problem.

Generalization is the main desired characteristics of ANN. It is a critical issue in developing artificial neural network. ANN can suffer from either under fitting or over fitting. Neural network with too many neurons may lead to over fitting and lose its generalization ability. To avoid over fitting "validation stop" is used.

E. Output Variable

Output variable represents ATC from sending area to the receiving area, a single output variable.

F. Training Pattern Sets

Training pattern sets for inputs and targets are generated randomly by, RPF based solution methodology.

G. Result Analysis

Maximum relative perceptron error is defined as follows:

$$MAPE = (1/n) * \sum_{i=1,2,..,n} (| R_i - N_i | / R_i) \quad (21)$$

Where, R_i is Exact value of ATC from RPF and N_i is ATC estimated by neural network.

VI. CONCLUSION

ATC is required to be posted on publicly accessible web at a small regular interval well in advance before bid. This forces the system operator, to compute accurate and commercially viable ATC faster. Heuristic methods such as GA for determining ATC are normally proposed during planning stage and serves as offline optimization tool as they require large computation time. For nearly all real power systems, ATC calculation using CPF, OPF and RPF methods would also require an extraordinary amount of computation time and for this reason, simplified methods, even if they have less accuracy, needed to be used for real time applications. Power flow sensitivity based methods are fast, well demonstrated and useful for ATC determination and estimation due to its simplicity in calculation and speedy outcomes. Hence it is an immense potential method for real time application. But, Sensitivity based Fast ATC calculating algorithms are not accurate due to several assumptions and simplifications. Sensitivity, based on DC load flow, methods has a poor accuracy when X/R ratio is low. Accurate methods are found to be computationally intensive and time consuming. Alternatively, truly trained ANN model helps at driving almost instantaneous and practically accurate ANN-based ATC estimation, irrespective of some missing or noisy inputs. ANN based ATC estimator allows a system operator to publish ATC information immediately as system parameter changes. The review concludes that if the power system has X/R ratio more than 4, sensitivity methods can be used for ATC calculations. On the other hand ANN based ATC estimator can be used for all systems including X/R ratio less than 4 for real time applications.

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