Dynamic Available Transfer Capability (DATC) Computation using Intelligent Techniques

D. M. Vinod Kumar, and Ch. Venkaiah

***Abstract*--In this paper Dynamic ATC has been calculated using energy function based Potential Energy Boundary Surface (PEBS) method. For the effective use of power system under the deregulated environment, it is important to make a fast and accurate evaluation of the maximum available transfer capability (ATC). Transient stability assessment by time domain simulation method is a time consuming process. A novel Dynamic contingency screening method is discussed and critical contingencies are selected for the computation of Dynamic ATC in order to reduce the computational time. The information about the ATC is to be continuously updated in real-time and made available to the market participants through Open Access Same time Information System (OASIS). On the basis of ATC, Independent System Operator (ISO) evaluates the transaction. Thus the ATC must be computed fast and accurately. In this paper ATC has been computed for real time applications using two different neural networks viz., i) Back Propagation Algorithm (BPA) and ii) Radial Basis Function (RBF) Neural Network These two methods are tested on WSCC 3 Machine 9 bus system and New England 10 machine 39 bus system and results are compared with the conventional energy function based PEBS method.**

***Index Terms*-- Artificial Neural Networks, Dynamic Available Transfer Capability, Power System Deregulation, Stability Limits.**

I. Introduction

AVAILABLE transfer capability (ATC) quantifies the viable increase in real power transfer from one point to another in a power system. ATC calculation has predominantly focused on steady-state viability. Point-to-point transfer can be increased until equilibrium point quantities, given by a power flow, reach security limits. Generally the equilibriums are evaluated for a number of contingencies. Security limits typically include voltage thresholds, and limits associated with feeder thermal capacity and generator reactive power output.

In the dynamic realm voltage collapse conditions have been considered to yield realistic computation of ATC. Techniques based on Quasi Steady State (QSS) approximation of long term dynamics for determining voltage stability constraints have been proposed in [3], [4]. In [5] an iterative approach for calculating dynamic ATC was proposed. The method uses the trajectory sensitivities and is prone to full representation of the power system modeled as a set of differential algebraic –discrete equations. The application of the method is limited at this time to the evaluation of a single free parameter that can be used to yield marginally stable trajectories. Computational complexity for applications to large system has not been assessed at this stage of development.

To overcome this new optimization methodology based on non-linear programming techniques to assess dynamic ATC in real time environment is proposed in [6]. Here a static optimization approach is considered to assess dynamic ATC. The approach is prone to integrate in both static and dynamic security constraints. However the integration of transient stability constraints into ATC calculation is still a relatively new development.

Especially a few OPF based dynamic ATC algorithms are available although they are conceptually rather nice [7]. The main difficulty lies in how to deal with the differential equations arisen from the transient stability constraints in the optimization procedure. In [8],[9] differential equations are expressed as a sequence of difference equations in the time domain.

An existing optimization method cannot directly deal with the kind of problem, which contains both algebraic, and differential equation constraints. To discretize differential equations set to form algebraic equations, which can easily be incorporated into optimization problems as additional constraints [10] with the adaptation of trapezoidal rule. The transient stability constraints are converted into a set of algebraic equations such that conventional programming methods can be adopted. However since many algebraic equations with inter- variables corresponding to each time step are introduced the dimensions of the problems explode dramatically.

A methodology based on primal – dual Newton interior point method (IPM) with quadratic convergence for non-linear programming problems is introduced in [10][11] to solve the dynamic ATC optimization problem. But the problem is with the choice of initial values, and primal dual variables number increases with the system size. And the problem lies in computing the Jacobian and Hessian matrices due to the introduction of transient stability constraints.

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978-1-4244-1762-9/08/$25.00 ©2008 IEEE

Since it is more difficult to consider dynamic constraints directly, security constrained OPF is used [12] as an alternative approach to consider stability limits. The existence of stable equilibrium in post disturbance system is only a necessary condition of stability [13]. Thus it is also important to ensure that the system can safely make transition from the pre to post disturbance-operating point [14].

OPF based algorithms, which introduce a form of transient stability constraints, have also been proposed for computing dynamic ATC. They are conceptually rather nice, but result in a problem formulation of huge dimension.

In many power systems however, point-to-point transfer is not restricted by steady-state limits, but by undesirable dynamic behavior following large disturbances. The post-disturbance operating point certainly must be viable; but it is also important to ensure that the system can safely make the transition from the pre- to the post-disturbance operating point. Dynamic ATC is concerned with calculating the maximum increase in point-to- point transfer such that the transient response remains stable and viable.

In this paper, Potential Energy Boundary Surface (PEBS) method based on energy function algorithm has been considered for direct stability studies to calculate dynamic ATC. The proposed dynamic ATC method first performs numerical simulations to compute the energy margin using PEBS method. By increasing the power at source bus and load at sink bus energy margin at each power step has been calculated. This process continues until the energy margin is less than the pre specified threshold value.

For the effective use of power system under the deregulated environment, it is important to make a fast and accurate evaluation of the maximum available transfer capability (ATC) from a supply point to a demand point. An ATC assessment requires a repetition of (N-1) security assessment with constraints of thermal limits, voltage stability and dynamic (transient and small signal) stability under multiple supply / demand scenarios, and therefore, the necessary computational effort of ATC calculation becomes very large. Especially, ATC assessment with transient stability constraints (transient stability ATC) has a dominant part in overall computational cost of an ATC assessment. Thus transient stability assessment by time domain simulation method is a time consuming process. Dynamic Contingency Screening method is one of the counter measures for this computational problem. A novel Dynamic contingency screening method [15] is discussed and critical contingencies are selected. Dynamic ATC between a given source sink pair is calculated for each critical contingency. And the effective Dynamic ATC is minimum of all ATCs corresponds to critical contingencies.

The Available Transfer Capability (ATC) information is made available on a public accessible Open Access Same time Information System (OASIS). In real time power market operation ISO must compute and update hourly ATC values to be made available on the web. Hence, Dynamic ATC has been computed using Artificial Neural Network (ANN). In this paper ANN based BPA and RBF have been utilized. These methods are tested on New England 10 machine 39 bus system and Western System Coordinating Control (WSCC) 3 machine 9-bus system.

II. Energy Function Based PEBS Method for Transient Stability Studies

In transient stability, we are interested in computing the critical clearing time and energy margin when the system is subjected to large disturbances. The energy function methods have proved to be reliable and are considered as promising tool in dynamic security assessment.

The computation of (V_{cr}) maximum value of the potential energy component of V(x) along the trajectory of

$$\dot{x} = f^{F}\left(x(t)\right), \qquad 0 < t \le t_{cl} \qquad (1)$$

$$x(o) = x_o$$

known as the potential energy boundary surface (PEBS) method.

The computation of critical clearing time (t_{cr}) :

1. Computing x_s, the stable equilibrium points of the post fault system given by
$$\dot{x} = f\left(x(t)\right), \qquad t > t_{cl} \qquad (2)$$
2. Formulating $V(x)$ for eq. (2). Generally, $V(x)$ is the sum of kinetic and potential energies of the post fault system, i.e., $V(x) = V_{KE} + V_{PE}$
3. Computation of V_{cr}: In PEBS method V_{cr} is obtained by integrating the faulted trajectory eq. (1) until the potential energy part V_{PE} of $V(x)$ reaches a maximum $V_{PE}^{\max}$. This value is taken as V_{cr} in the PEBS method. In controlling unstable equilibrium point (u.e.p) method, integrate eq. (1) for a short interval followed by either a minimization problem to get the controlling u.e.p, or integration of reduced order post fault system after the PEBS is reached to get the controlling u.e.p x^u. V_{cr} is given by $V_{cr}\left(x^u\right) = V_{PE}\left(x^u\right)$, since V_{KE} is zero at an u.e.p.
4. Calculating the time of instant t_{cr} when $V(x)$= V_{cr} on the faulted trajectory of eq (1). The faulted trajectory has to be integrated for all the three methods to obtain t_{cr}. In PEBS method, the faulted trajectory is already available while computing V_{cr}. Hence, the computation time is least for the PEBS method.

In this paper PEBS method has been considered to compute V_{cr}, t_{cr} and energy margin.

MODELING ISSUES

In transient energy function technique, we must consider the model in two time frames, as follows:

1. Faulted system

$$\dot{x}=f^F\left(x(t)\right), \qquad 0<t\le t_d \tag{3}$$

2. Post fault system

$$\dot{x}=f\left(x(t)\right), \qquad t>t_d \tag{4}$$

In reality, the model is a set of differential – algebraic equations (DAE), i.e.,

$$\begin{aligned}\dot{x}&=f^F\left(x(t),y(t)\right)\\ 0&=g^F\left(x(t),y(t)\right), \qquad 0<t\le t_d\end{aligned} \tag{5}$$

The function 'g' represents the nonlinear algebraic equations of the stator and the network, while the differential equations represent the dynamics of the generating unit and its controls. There are methods like Reduced order models, such as flux decay model and classical models have been presented. In the classical model representation, we can use either preserve the network structure (structure preserving model) or eliminate the load buses (assuming constant impedance load) to obtain the internal node model. Structure preserving models involve nonlinear algebraic equations in addition to dynamic equations, and can incorporate non linear load models leading to the concept of structure preserving energy function (SPEF) $V(x,y)$, while models consisting of differential equations lead only to closed form types of energy functions $V(x)$.

III. Energy Function Formulation

Analytical Lyapunov functions can be constructed only if the transfer conductance's are zero, i.e. D_{ij}=0. Since these terms have to be accounted properly, the first integrals of motion of the system are constructed, and these are called energy functions. There are two options, to use either the relative rotor angle formulation or the center of inertia formulation. The latter, option has been utilized since there are some advantages [2]. Since the angles are referred to a center of inertia, the resulting energy function is called the transient energy function (TEF).

In this formulation, the angle of the center of inertia (COI) is used as the reference angle, since it represents the "mean of motion" of the system. Although the resulting energy function is identical to $V\left(\delta,\omega\right)$ (using relative rotor angles), it has the advantage of being more symmetric and easier to handle in terms of the path dependent terms. Synchronous stability of all machines is judged by examining the angles referenced only to COI instead of relative rotor angles. Modern literature invariably uses the COI formulation. The energy function in the COI notation, including D_{ij} terms (transfer conductances) was proposed.

Energy Margin (EM) =V_{cr} -V_{cl} is shown in Fig. 1 (the total and potential energies of the system when fault is on bus 5 of three machine 9-bus system). The Energy margin, critical clearing time and critical energy are shown in Table-I for fault clearing time T_{cl} = 0.05 sec.

TABLE - I

V_{CR}, T_{CR} AND EM FOR DIFFERENT FAULTS

(FAULT CLEARING TIME T_{CL} = 0.05 SEC, 3 MACHINE 9-BUS SYSTEM)

Fault Bus	Line to be removed	Critical Clearing Time (T_{cr})	Critical Energy (V_{cr})	Energy Margin (EM)
4	4 to 6	0.232	1.5642	1.4943
5	5 to 4	0.253	1.1756	1.1234
6	6 to 9	0.196	0.32135	0.30468
7	7 to 5	0.11	0.35059	0.3446
8	8 to 9	0.256	1.9398	1.9393

Total and potential energies of the system and rotor angles with respect to time for different faults has shown below.

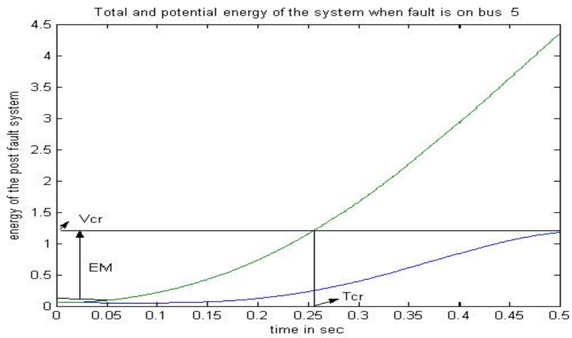

Fig. 1. Computing EM, V_{cr},T_{cr} from the graph (Fault on bus – 5).

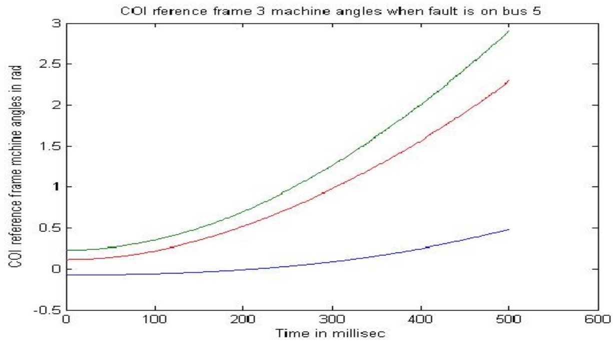

Fig.2. COI reference machine angles (Fault on bus -5).

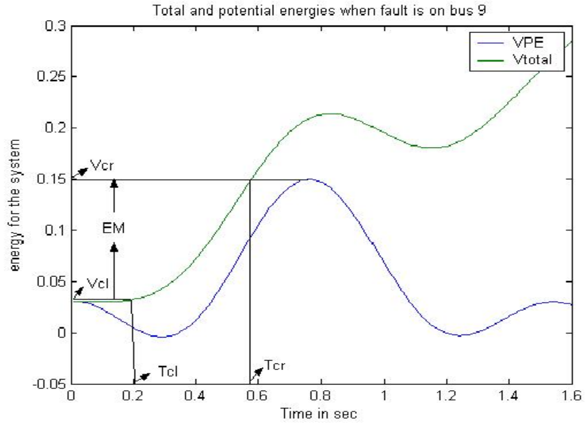

Fig. 3. Computing EM, V_{cr},T_{cr} from the graph (Fault on bus -9).

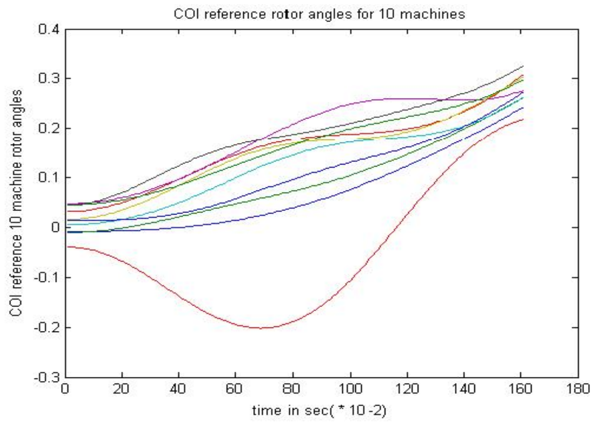

Fig. 4. COI reference machine angles (Fault on bus -9).

IV. Computation of Dynamic Contingency Screening

For the effective use of power system under the deregulated environment, it is important to make a fast and accurate evaluation of the maximum available transfer capability (ATC) from a supply point to a demand point. An ATC assessment requires a repetition of (N-1) security assessment with constraints of thermal limits, voltage stability and dynamic (transient and small signal) stability under multiple supply / demand scenarios. Therefore, the necessary computational effort of ATC calculation becomes very large. Especially, ATC assessment with transient stability constraints (transient stability ATC) has a dominant part in overall computational cost of an ATC assessment. Thus transient stability assessment by time domain simulation method is a time consuming process. Dynamic Contingency screening method is one of the counter measures for this computational problem. Fast contingency screening is expected to be an integral part of any practical on-line dynamic security analysis (DSA). Ranking of contingencies requires the use of severity indices, and for DSA such an index must be a measure of stability. From experience in static security analysis, it is well known that some indices work better than others for particular power systems and those combinations of indices usually work better than a single index. For DSA, which are still in its infancy, severity indices are more complex and very few have been tested for screening. Several indices are proposed for contingency screening in online DSA [15]. These indices are based on the concepts of coherency, transient energy conversion between kinetic energy and potential energy, and three dot products of system variables. Dynamic ATC was found for each screened critical contingency, and the effective Dynamic ATC is minimum of all ATCs.

Algorithm for Proposed Contingency Screening

1. Select the possible (N-1) contingencies; say there are N possible contingencies.
2. For contingency=1, find the energy margin (EM), (discussed in section III). This energy margin is ΔV
3. While integrating the faulted system equations, find the difference between V_{KE} and V_{PE} at each time step, and maximum value of these differences is to be noted. This maximum value is ΔV_{KE} .
4. Then compute the proposed index as,

$$\Delta V_n = \Delta V \big/ \Delta V_{KE}$$

$$\text{Proposed index (PI)} = 1 \big/ \Delta V_n$$

Where,

ΔV = Transient energy margin (The difference of the energy at the controlling unstable equilibrium point and at fault clearing)

ΔV_{KE} = Kinetic Energy

5. Find the Proposed index for every contingency, and arrange them in descending order. If the PI is high, severity of contingency is high and it should be given first rank. Rank all the N contingencies using the PI. Five critical contingencies are selected out of the N contingencies. These five critical contingencies affect the Dynamic ATC between a pair of source and sink.

Contingency screening using the proposed index (PI) for the New-England 10 machine 39-bus system has been used for simulation. Here, 27 (N-1) credible contingencies are considered and 5 critical contingencies are selected based on proposed index, shown in Table-II.

TABLE - II
SELECTED CRITICAL CONTINGENCIES

Fault Bus	Line to be removed	Proposed Index
1	39 to 1	1.0058
3	3 to 4	0.87808
9	9 to 39	0.86735
7	7 to 8	0.8654
14	14 to 15	0.84222

V. Computation of Dynamic ATC (DATC) for Selected Critical Contingencies

Algorithm for computation of dynamic ATC

1. Select a source bus and sink bus between which Dynamic ATC to be calculated.
2. Select the first critical contingency, and read the corresponding fault bus and line to be removed to clear the fault.
3. For the first contingency and the base case loadings, find the energy margin (EM).
   While (EM>thresh hold value(0.1)),
   Increase the source bus power and sink bus power with power step of 0.1 p.u.
   and find the energy margin (EM).

4. If (EM<thresh hold value), then Dynamic ATC is the difference between source bus power after series of increments and base case source bus power
5. Repeat the steps (3) and (4) and calculate Dynamic ATC for each critical contingency.
6. Effective Dynamic ATC between given source sink pair is minimum of all Dynamic ATCs, which corresponds to critical contingencies

VI. SIMULATION AND RESULTS

The WSCC 3 machine 9-bus system and New–England 10 machine 39-bus system has been considered for simulation of Dynamic ATC calculations. Dynamic ATC for different source and sink pair of transactions has been calculated and the results are presented below.

A. *CASE-I*

DYNAMIC ATC (WSCC 3 MACHINE 9 -BUS SYSTEM) FOR SELECTED CRITICAL CONTINGENCIES

TABLE - III
TRANSACTION BETWEEN SOURCE BUS 2 AND SINK BUS 5

Fault Bus	Line to be removed	Dynamic ATC (p.u.)
4	4 to 6	0.89
5	5 to 4	0.59
6	6 to 9	0.26
7	7 to 5	**0.17**
8	8 to 9	0.96

Dynamic ATC between bus 2 to 5 is = **0.17 p.u**.

B. *CASE-II*

DYNAMIC ATC (NEW-ENGLAND 10 MACHINE 39 BUS SYSTEM) FOR SELECTED CRITICAL CONTINGENCIES

TABLE - IV
TRANSACTION BETWEEN SOURCE BUS 34 AND SINK BUS 11

Fault Bus	Line to be removed	Dynamic ATC (p.u.)
1	39 to 1	2.8
3	3 to 4	5.1
9	9 to 39	**2.5**
7	7 to 8	4.9
14	14 to 15	4.6

Dynamic ATC between bus 34 to 11 = **2.5 p.u**.

VII. DYNAMIC ATC COMPUTATION USING ARTIFICIAL NEURAL NETWORKS

In the restructured power market, the consumers can choose their power supplier. The transmission system becomes critical element of power system. To utilize transmission system effectively the information about ATC must be known to the Independent System Operator (ISO). Hence, the information about the ATC should be made available on OASIS, which is accessible to consumers and to the utilities. ATC values posted on the OASIS should be updated at a specified time interval. The value of ATC determines the further commercial activities of system, over cautious conservative estimation of it may lead to inefficient utilization of transmission network. So, it must be calculated fast and accurately. ATC assessment with transient stability constraints (transient stability ATC) has a dominant part in overall computational cost of an ATC assessment, as transient stability assessment by time domain simulation method is a time consuming process. Even calculation of Dynamic ATC using energy function based method will also take more time. To reduce the computational time, Back-Propagation Algorithm (BPA) based on Feed forward Neural Network and Radial Basis Function Neural Networks have been utilized to compute the Dynamic ATC.

A. *Selection of Input variables*

Dynamic ATC between a given pair of source-sink buses in a large system is determined using five inputs. These are source bus injection (P_s), loading index (γ) for the base case, fault bus (FB), base flow in the line (LF), which is to be removed to clear the fault, and fault clearing time (t_{cl}). The Dynamic ATC problem for real-time power market application has been attempted using two different algorithms i) Back Propagation Algorithm and ii) Radial Basis Function Approach.

B. *Implementation*

The New-England 10 machine 39-bus system has been used to compare the performance of proposed methods with that of energy function based PEBS method for Dynamic ATC determination. The pair of buses 36 (source) and 21(sink) is considered for illustrating the determination of ATC.

C. *Generation of Patterns*

The Training and testing patterns are generated using energy function based PEBS method by treating bus 36 as source and 21 as sink. These patterns are generated by randomly varying the 5 inputs with in the min and max limits.

D. *Training*

Training sets provided to the neural network are representative of the whole state space of concern so that the trained system has the ability of generalization. Training patterns for the New – England 10 machine 39-bus system are composed of different fault cases, fault clearing times and loadings. 500 patterns were used for training the network.

E. Testing

The trained neural network was tested using 50 patterns that are composed of different fault cases, fault clearing times and loadings. None of these patterns were used in the training of the neural network.

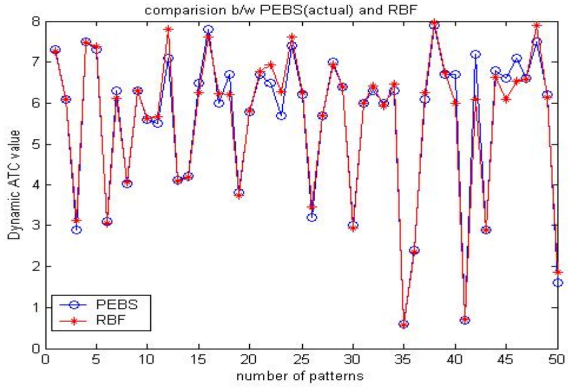

Fig. 5. Comparison of RBFNN D-ATC and PEBS based DATC.

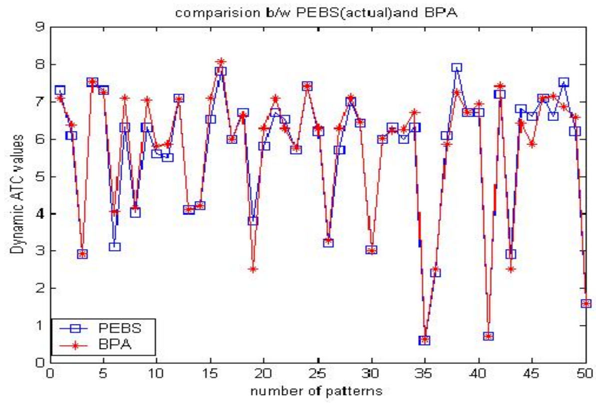

Fig. 6. Comparison of BPANN D-ATC and PEBS based DATC.

VIII. Conclusions

In this paper, for the accurate estimation of ATC stability limits have been considered in addition with the static limits. Energy function based Potential Energy Boundary Surface (PEBS) method has been considered for determining Dynamic ATC. Transient stability assessment by time domain simulation method is a time consuming process. Critical contingencies are selected based on Dynamic contingency screening. Dynamic ATCs for different transactions of WSCC 3 machine 9-bus system and New-England 10 machine 39-bus system have been calculated using PEBS method. The selected critical contingencies have been used to compute the effective Dynamic ATC value between a pair of source and sink bus.

The Dynamic ATC has been computed using, Artificial Neural Networks viz., Back Propagation Algorithm and Radial Basis Function Neural Networks. The results are compared with the PEBS method. The proposed methods have been tested on New-England 10 machine 39-bus system, and results are compared with that of energy based PEBS method. The mean normalized error for BPA and RBF is 0.050192, and 0.028587 respectively. Hence, the Radial Basis Function (RBF) Neural Network based Dynamic ATC, can be used for power system deregulated real-time applications.

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