Dynamic Stability and Network Constrained Optimal Spinning Reserve Allocation

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***Abstract*—this paper presents an integrated work for regulation reserve allocation considering dynamic stability and load variations. In deregulated power system, participants compete to maximize their surplus without considering system stability margin, which forces the power system to operate closer to their instability boundaries. Suitable spinning reserve amount and allocation to meet additional load demand and the corresponding power flows through transmission lines at acceptable stability margin is an important aspect for a secure power system operation following a credible contingency. The geographical localization and coordination of the available amount of spinning reserve used for regulation must be based on accurate online system state to cover the uncertainty associated with electric demand. The target is to minimize the cost of spinning reserve considering system operational constraints independent on the energy market auctions. This target is achieved by using a mixture of a modified particle swarm optimization (PSO) and artificial neural network (ANN). ANN is used to assess power system stability to shortage the computation time. The rescheduling process based on the generation companies The critical clearing time (CCT) at the critical contingency is considered as an index for transient stability. System minimum damping of oscillation (MDO) is considered as indicator for oscillatory stability. The proposed framework has been applied on a 66-bus test system.**

***Index Terms*-- Power system dynamic stability, Power generation economics, Security and energy pricing, Up and down-spinning reserve**

I. INTRODUCTION

THE spinning reserve amount and allocation are critical issues to meet the variation of forecasted load with an acceptable security level due to operating the large scale interconnected power system near its limits. The load variation may violate the standard stability limits if the available instantaneous regulation reserve is not sufficient to obtain the power balance at an acceptable stability level. In addition, sudden disconnection of generator should be followed by instantaneous supply of the available spinning reserve to avoid cascaded failure of equipments due to overloading. Power system deregulation forces the system operator to determine the required spinning reserve based fair and equitable market strategy. The operator has the responsibility of maintaining adequate spinning reserves in the system, not only on a total-MW bases, but also needs to take care of the location aspect of this reserve, taking into account transmission capacities available in the system [1]. Spinning reserve can be determined in a separate market to ensure system security or via an integrated market for energy and ancillary services [2][3]. The electric power demand is considered fixed during day-ahead spinning reserve allocation in many literatures where and errors in forecasted load or generator outage may lead to overload due to the limitations of system transmission capacities [4]. In this paper, the hourly probability that the forecasted electric demand is changed in random distribution is considered during specifying the proper amount and allocation of spinning (regulation) reserve. The coordination of available regulation reserve to meet the change in forecasted demand may prevent violation of system security levels during credible contingencies without load shedding.

A market clearing mechanism is proposed to allocate the spinning reserve not only cost of spinning reserve but also system dynamic stability. This market is proposed to determine the proper cost at each period to ensure system stability and power balancing while minimizing the cost of unused reserve power. The power system stability is assessed based transient stability and small signal stability. Transient stability assessment (TSA) becomes a major concern because a fault, error in forecasted load or loss of a large generator can lead to large electromechanical oscillations between generating units that may rise to loss synchronism. Critical oscillatory modes appear after small disturbances limit the amount of power that can be transferred and may lead to power system breakup and outage. The oscillatory stability assessment (OSA) can be characterized in terms of mode parameters, e.g. frequency and damping of oscillations to improve system state. Including dynamic behavior in spinning reserve allocation helps system operator to secure the system operation after the disturbances and move into an acceptable steady-state condition that meet all established limits. In the proposed market, Artificial neural network (ANN) is used as fast and accurate tool to include the dynamic stability assessment during the market clearing to shorten the calculation time required. ANN is trained to map the power system operating conditions in order to simulate the dynamic system behavior [5][6]. In this paper ANN designed to be a robust assessment tool for TSA and OSA which can deal with all expected changes in power distributions and system topology. In this market, suppliers participant in the market by offering their spinning energy bids. These bids should specify up or down generation capability and the corresponding costs.

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The problem is formulated as a constrained global optimization problem and is solved by a mixture of particle swarm optimization (PSO) and ANN. Operating limits based on current conditions and energy market clearance are used to achieve the required spinning reserve at enhances power system dynamic stability. Critical fault clearing time (CCT) characterizing transient stability and minimum damping of oscillation (MDO) characterizing oscillatory stability are considered as additional constraints within the optimization process and estimated using offline trained ANN.

II. PROPOSED ALGORITHM

A. Spinning reserve specification

The conventional way to determine the total amount of spinning reserve is based on the largest online generator or a specified fraction of the peak load. Up reserve is related loss of generators and down reserve is related to sudden decrease in electric demand. The random availability of disconnecting generating units provides a challenge to specify the proper allocation of required total spinning reserve. Therefore, the probability of random generating unit may lead to a significant sacrifice of system security and reliability or load shedding.

In the paper, PSO is used to allocate the total spinning reserve among suppliers who participate in the market considering the effect of expected outage of generators. Each outage is considered as a disturbance scenario and the spinning reserve is allocated to obtain power balance at an acceptable stability level. This method helps to reduce the probability of loss of load during abnormal operating conditions where the available spinning reserve is distributed based on a random loss of connected generators. This spinning reserve market is considered as a separate market established after the hour-ahead energy market clearance to specify the proper spinning reserve at the next loading period. The framework of the proposed approach is sketched schematically in Figure 1.

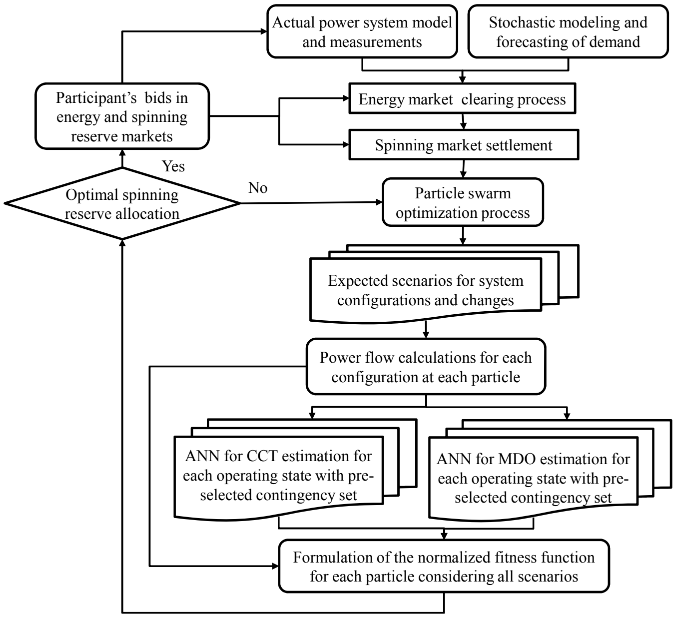

Figure 1: Framework of the proposed approach

B. Problem Formulation

The problem is formulated as cost minimization objective function of a single period to specify the optimal allocation of the spinning reserve can be described as follows:
Minimize:

$$\text{Max.}\ (C_k = \sum_{i=1}^{N_g} w_i C_i(P_{gi}^{SR}) \quad k = 1,2, \dots N_S) \tag{1}$$

Power flow constraints

$$\boldsymbol{h}(\mathbf{x}) = 0 \tag{2}$$

$$\boldsymbol{g}(\mathbf{x}) \leq 0 \tag{3}$$

Unit spinning reserve capacity and ramping constraints

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \tag{4}$$

$$P_{gi}^{SR} \leq P_{gi}^{SR_{max}} \leq P_{gi}^{max} - P_{gi} \tag{5}$$

$$P_{gi}^{SR} \leq P_{gi}^{Ramp_{max}} \tag{6}$$

$$\sum_{i=1}^{N_g} P_{gi}^{SR} \geq P^{SR_{max}} \tag{7}$$

Dynamic stability constraints

$$CCT > CCT_{min} \tag{8}$$

$$\xi > \xi_{min} \tag{9}$$

Where, C_k is the total cost of required spinning reserve at working scenario k of $\mathrm{N_S}$ scenarios for system configuration changes, C_i is the cost based on participant's bids of N_g participates in spinning reserve market. P_{gi}^{SR} is the spinning reserve contributed by unit i. w_i is index of participation with 1 or 0. $\boldsymbol{h}$ represents power balance equations at all nodes. $\boldsymbol{g}$ represents voltage and current limitations within the grid. $\mathbf{x}$ is the vector of control variables including transformer tap-settings, load variations and generated active and reactive power. P_{gi}^{min}, P_{gi} and P_{gi}^{max} are the minimum output, current output and maximum output of generator i. $P_{gi}^{SR_{max}}$ and $P_{gi}^{Ramp_{max}}$ are maximum offered spinning reserve and maximum ramp rate of unit i. CCT_{min} is the acceptable minimum CCT. ξ is the damping of oscillation and ξ_{min} is the acceptable MDO.

In addition to the aforementioned constraints, the possibility for insufficient generation to meet the load in case of disconnecting generating unit can be considered as a contingency effect constraint when the generation and spinning reserve from this unit will be equal to zero. This leads to increase in the total required spinning reserve quantity. The participants in the market submit their volunteer energy bids including energy limits and the corresponding cost functions. These offered biddings can be implemented with any acceptable bidding form such as multi-stage linear or step bid strategy.

III. OPTIMIZATION PROCESS USING PSO

PSO is a population based optimization technique was introduced by Kennedy and Eberhard in 1995 to simulate the bird flock and is used to solve many problems in the field related power systems [7]. The standard procedure of PSO algorithm is presented in Figure 2, which can be easily implemented with few coding lines.

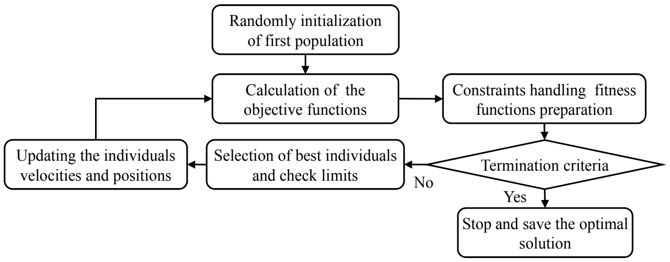

Figure 2: The basic steps of standard PSO algorithms

Optimization process based PSO is used to obtain the optimal spinning reserve allocation to for power balancing at acceptable dynamic stability level during pre-defined set of credible contingencies with minimum cost. During the optimization process, the particles move through hyperspace defined by the limits of the control variables and updated to satisfy all constraints. Constraints handling method is a highly important. The problem should be transferred into unconstrained problem by constructing a constrained fitness function, which incorporates penalty function for any constraints violation. Many self-adaptive penalty functions are proposed for constraints handling. In [8] a self-adaptive penalty function based algorithm for constrained optimization in implemented to achieve this target and is used in this paper with a new selection strategy to be suitable for comparison between normalized fitness function during iterative process. The comparison depends on the fitness function, which is built based on the information available from two different measures of different scale, the objective function and the total constraint violation. The selection strategy is presented in Figure 3 and the application to select the local best position of each individual and global best position during the iterative process can be summarized by:

Case 1: when the current position and the previous local best position of individual are infeasible, the selection of the new best position evaluated based on the normalized fitness values according to the following equation.

$$\varphi_i(\mathbf{x}) = \sqrt{\varphi_{in}(\mathbf{x})^2 + v^2} + (1 - r_f) \cdot v + r_f \cdot \varphi_{in}(\mathbf{x}) \qquad (10)$$

$$\varphi_{in}(\boldsymbol{x}) = \frac{f(\mathbf{x}) - f_{min}(\mathbf{x})}{f_{max}(\mathbf{x}) - f_{min}(\mathbf{x})} \qquad (11)$$

$$v = \frac{1}{N_c} \sum_{m=1}^{N_c} \frac{viol_m}{viol_{m,max}} \qquad (12)$$

where $\varphi_i(\mathbf{x})$ is the constrained fitness. $f(\mathbf{x})$ is a scalar value objective function in the current iteration with a minimum value $f_{min}(\mathbf{x})$ and maximum value $f_{max}(\mathbf{x})$. v and $viol$ are the average constraints violation and violation of each constraint. N_c equality and inequality constraints violation of each individual. r_f is the ratio of the feasible individuals in the current population.

Case 2: when current position of the individual is feasible and the best local position is infeasible, the current position is selected a new local best position

Case 3: If both the current position and the previous local best position are feasible, the selection of the new local best position is based the comparison between the original objective values.

Case 4: if the current position is infeasible and the previous local best position is feasible, the new local best position is the same as the previous local best position.

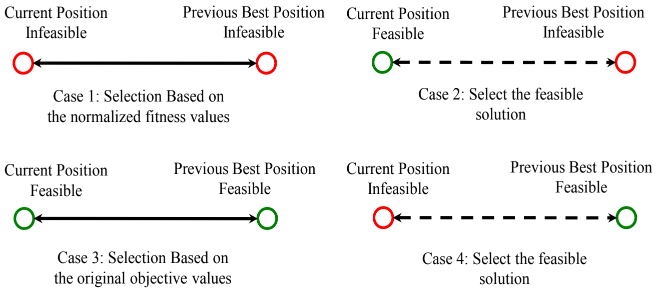

Figure 3: Selection strategy for the local and global best positions

Participant's bids to provide spinning reserve should be submitted with bids for hour-ahead energy market and objective function formulated with this bids after hour-ahead energy market clearance. The bids represent the cost of the unused allocated spinning reserve where the participants will paid the market clearing price when the reserve energy is generated and used. The population in PSO is initiated with a dimensional vector of control variables including active and reactive power of all participants in the market in addition to all online available control variables. The target is to obtain the spinning reserve allocation to anticipate the disconnection of each generator in a pre-selected set at an acceptable dynamic stability level without loss of load.

For each particle in the population, the spinning reserve distribution is applied into expected disconnecting scenarios. In this paper, a set of expected disconnection of generators is used to represent the system configuration to select the best distribution of spinning reserve. AC power flow is used to adjust each operating point. Each power system configuration is subjected to a set of selected critical contingencies to investigate the power system dynamic stability. Based on the selected features, offline trained ANNs are used to estimate CCT and MDO. After ranking, when the minimum CCT and/or damping ratio are less than the desired values, it considered as constraints violation during optimization. Thus, the constrained objective function is formulated and velocities and positions of particles are updated. The optimization process continued until reach the stopping criteria in the direction to enhance the system dynamic stability with minimum cost. The final solution should make all potentially critical contingencies completely stable at the same time. The used code for PSO was implemented by MATLAB software.

IV. STUDY POWER SYSTEM

The implementation of the proposed framework is illustrated through the Power Stability Test 16-machine network (PST16) [9]. The single line diagram of the test system is shown in Figure 4. The test system contains 66-bus and is divided into three areas (A, B and C) connected through tie lines. The generators are considered hydropower and thermal power types and consist of number of blocks as shown in the figure. Each block in area A is rated 220 MVA with a maximum ramp rate per minute to supply the cleared spinning reserve of 15 MW. Each block in area B is rated 259 MVA with a maximum ramp rate per minute period to supply the cleared spinning reserve of 20 MW. Each block in area C is rated 247 MVA with a maximum ramp rate per minute period to supply the cleared spinning reserve of 18 MW. The generator models are fifth order model with detailed exciter and governing systems.

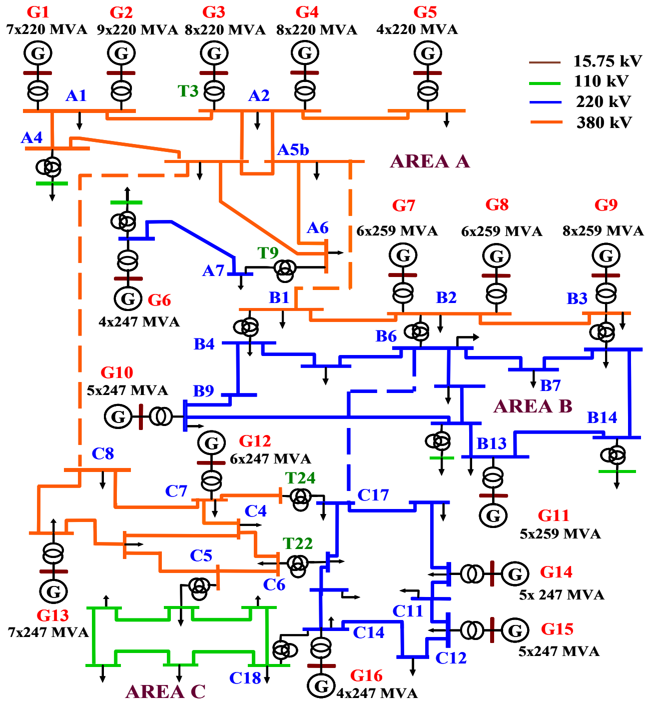

Figure 4: Single line diagram of the sixteen-machine, 66-bus test system

V. GRID DYNAMIC BEHAVIOR EVALUATION

ANN modeling to assess the power system dynamic is sensitive to the data used in calibration, which should be collected carefully. Time domain simulation (TDS) is known method that provides accurate calculations of the time response of the electrical signals during contingencies by solving the nonlinear systems set of differential algebraic equations through step-by-step integration by producing time response of all state variables. Transient stability is studied in this paper based on coherent behavior of generators relative rotor angles procured from TDS outputs. The deviation of the relative rotor angles beyond a pre-defined limit following contingencies may produce of loss of synchronism among generators. The fault duration corresponding to this situation is giving useful information about system transient stability assessment. The CCT is the maximum time duration that a fault may occur in power systems without failure in the system to recover to a steady state operation.

Power system oscillatory stability is also important during spinning reserve allocation because the calling of spinning reserve during disconnection of generator may lead to congestion in transmission lines. Therefore, any small disturbance may lead to a critical mode of oscillation, which limit the transmission line capability and may lead to system instability. In order to account for effects of the increase of system non-linearity on oscillating modes, Prony analysis is used to estimate the minimum damping of oscillation at each operating point. Prony analysis is a curve-fitting methodology that extends Fourier analysis by directly estimating the frequency, damping, strength, and relative phase of the modal components present in a recorded signal [10]. Dynamic system identification toolbox (DSI) is used to identify system oscillation and damping during injected probing signals [11].

The modeling and simulation results for load flow and dynamic simulation at a pre-selected set of contingencies are done by using the simulation package 'Power System Dynamics (PSD)' [12]. The collected data at each operating point and corresponding CCT are used to train ANN for transient stability assessment during spinning reserve allocation. The same procedure used in [13] for designing two ANNs for transient stability assessment and oscillatory stability assessment is used in this paper.

VI. NUMERICAL RESULTS

The implementation of the proposed approach is illustrated through the PST16 presented in section IV. The energy market clearing schedule, the spinning reserve offers and ramp rates are presented in Table I.

TABLE I
SCHEDULE POWER FROM ENERGY MARKET AND SPINNING RESERVE LIMITS

Generator name	Generation schedule (MW)	Total ramp rate (MW/ Min)	Maximum reserve Limit	Cost of reserve	
				(€/h)	(€/MW/ h)
G1	773.2	55	240	20	2.9
G2	1021.7	40	130	60	2.2
G3	1383.8	40	140	35	4.5
G4	1304	55	220	70	2.5
G5	422	30	90	35	5.6
G6	797.3	40	100	46	3.5
G7	1240.5	60	135	60	4.3
G8	1196	55	130	70	5.2
G9	920.77	40	140	100	5.9
G10	1151.9	30	125	76	8.1
G11	1367.2	50	90	45	3.8
G12	1495.3	40	70	65	8.5
G13	1272	45	120	90	2.8
G14	1169.4	55	135	150	4
G15	1349.6	35	120	120	4.5
G16	1093.8	40	115	140	3.5

In the selected operating point, the energy market is cleared for the next single period with a maximum generating unit of 1495.30 MW. Therefore, the spinning reserve is assumed not less than 1500 MW. Self-clearance three-phase short circuit is considered as contingency to investigate the power system dynamic behavior of each scenario. The target for a dynamic stable system operation is assumed 150 milliseconds as a common critical fault time for all circuit breakers in the system and the acceptable sufficient minimum damping of oscillation is 4%.

All suppliers are assumed participate in the spinning reserve market with energy bids and provide the reactive power service to support the grid voltage without additional costs and participate in the market. Two generators from each area with highest schedule power are assumed to be disturbed and disconnected to obtain 6 scenarios with different configuration to study the effect of calling the allocated spinning reserve on the system limits and dynamic stability.

Table II shows the distribution of the required spinning reserve without dynamic stability consideration and with power system dynamic stability consideration during spinning reserve allocation and the corresponding total cost.

TABLE VII

POWER GENERATION (MW) BEFORE AND AFTER RESCHEDULING PROCESS

Generator name	Reserve without stability (MW)	Reserve cost (€/h)	Reserve with stability (MW)	Total cost (€/h)
G1	210.5	630.45	150.6	456.74
G2	123.8	332.36	94.8	268.56
G3	120.8	578.6	100.2	485.9
G4	114.2	355.5	86.5	286.25
G5	84.7	509.32	81.6	491.96
G6	101.5	401.25	96.02	382.07
G7	95.6	471.08	115.3	555.79
G8	50.3	331.56	120.4	696.08
G9	52.6	410.34	132.03	878.977
G10	31.5	331.15	97.2	863.32
G11	89.7	385.86	80.4	350.52
G12	50.6	495.1	55.2	534.2
G13	92.5	349	100.5	371.4
G14	105.3	571.2	97.5	540
G15	110.3	616.35	124.7	681.15
G16	115	542.5	35.8	265.3
Total cost (€/h)		6681.17		8108.22

The total cost for spinning reserve allocation is increased from 6681.17 (€/h) to 8108.22(€/h) due to the considering of dynamic stability beside the network constraints. In this case the some participants with low cost bidding may be not able to selected and participants with higher bidding cost may be selected to stabilize the system following a credible disturbance during abnormal conditions. This consideration is very important for securing the power system following disconnecting generator or sudden increase of eclectic demand. Table III presents the values of CCT and MDO during disconnecting of two generators from each area where optimal power flow is used to schedule the spinning reserve.

TABLE III

DYNAMIC STABILITY ASSESSMENT DURING CALLING OF RESERVE

	Disconnected generators					
	G1	G3	G7	G10	G12	G14
CCT (ms)	171.8	153.5	161.2	171.6	150.2	156.4
MDO (%)	5.3	4.8	4.2	7.3	4.3	7.8

VII. CONCLUSION

Including power system dynamic behavior into consideration during spinning reserve allocation beside the network constraints is presented in this paper. Considering system dynamic in spinning reserve market allocation will alleviate the effect of contingencies and maintain the system away from its stability limits. In the market, participants introduce their offers and PSO-ANN is used as optimization tool to find a solution to allocate the required level of spinning reserve at enhanced dynamic stability with minimum payments for participants in the market. ANN is used as tool for TSA and OSA reducing the time consumed during repeatedly calculations and traditional method can be used in the calculation time is not a critical issue. The ANN should be trained for all expected load condition and system configuration to enhance the accuracy of estimation for system stability. The results emphasize PSO capability of handling nonlinear mixed-integer optimization problems with complex objective function and constraints such as spinning reserve allocation using AC power flow with including all constraints. The results show that the spinning reserve allocation considering system stability beside all system constraints can be used as a control action for securing the system operation.

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