POWER-FREQUENCY TRANSIENT STUDIES USING DYNAMIC ENERGY BALANCE

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Abstract- Dynamic Energy Balance is a new technique for power system dynamic simulation. It requires about one tenth the computational effort of a Transient stability study yet gives similar results so far as frequency transients are concerned. Applications, methodology and comparison with a transient stability study are treated in this paper.

I. INTRODUCTION

The development of dynamic energy balance studies is motivated by the need for more economical dynamic simulation of power frequency transients. From a computational viewpoint this amounts to a search for ways to avoid the small integration time steps which characterize transient stability studies. The inclusion of generator sub transient phenomena, damper windings, and/or small excitation system time constants sets a very low upper limit to step size, but this can be increased by appropriate choice of dynamic models. Hence, the ultimate limit to step size in transient stability studies is the frequency of synchronizing oscillations. Conceptually, the approach taken in dynamic energy balance is quite straightforward. Eliminate synchronizing oscillations from the dynamic model, avoid small time constants in the representation of subsystems, and increase integration step size.

D.E.B principles are based on the assumption that there is only one system center of inertia and each generator is assumed to have same angular acceleration as the system center of inertia. This helps in representing all the rotating masses by one equivalent rotating mass, there by only one swing equation is needed to solve for rotor dynamics. With the above assumptions, the synchronizing oscillations would be eliminated there by enabling the use of large time steps of integration resulting in reduced computational effort.

In the D.E.B model, conventional power flow solution along with slack bus representation is repeatedly used to estimate the electrical power generated in the system. Therefore the computational efficiency is greatly dependent on the speed of solution of the power flow method in spite of solving only one set of coupled first order differential equations of the equivalent rotating mass of the power system along with the associated sub component dynamic equations. The power flow method used was based on Fast Decoupled Load Flow model using triangular factorization and programmed to exploit sparsity.

Dynamic energy balance can be applied directly and efficiently to problems arising from power-frequency transients. System response to loss of generation or load and the behaviour of load-frequency control are two such problem areas.

II. METHODOLOGY

1. Mathematical Model

During transient conditions, the entire system is assumed to have an equivalent speed 'ω_0' which will be equal to the inertia weighted average of individual generator rotor speeds. This equivalent speed of the system is defined as the velocity of the system center of inertia. The center of inertia is the rotational analog to the center of mass and is referred to as system center of angle θ_o. The center of angle θ_o is defined as,

$$\theta_0 = \frac{1}{M_T}\sum M_j\theta_j \qquad (1)$$

$$M_T = \sum_{j=1}^{n} M_j$$

The dynamic equations of motion of system center of inertia are as follows:

$$\dot{\omega}_0 = \left(P_{mT} - P_{eT}\right)/M_T \qquad (2)$$

$$\dot{\theta}_0 = \left(\omega_0 - \omega_s\right) \qquad (3)$$

Where $P_{mT} = \sum_{j=1}^{n} P_{mj}$

$$P_{et} = \sum_{j=1}^{n} P_{ej}$$

The frequency 'f_0' ($\omega_0=2\pi f_0$) obtained by the solution of equation (2) is the inertia weighted average of frequencies of individual machine rotors present in the system. The above equations form the basis of simulation of power-frequency transients by dynamic energy balance concepts.

Assumption of P_{et} constant during these oscillations gives a scope for elimination of synchronizing

oscillations from the model. Elimination of these oscillations permits us to choose larger time steps of integration and this facilitates to study the slower dynamics of the power system.

Let Φ_j be the jth rotor angle measured with respect to system center of inertia. Then the rotor angle θ_j measured with respect to synchronous reference frame can be expressed as

$$\theta_j = \phi_j + \theta_0 \quad (4)$$

Now the jth rotor equation of motion is,

$$M_j \dot{\omega}_j = \left(P_{mj} - P_{ej}\right)$$

Can be re-written as

$$M_j\left(\ddot{\phi}_j + \ddot{\theta}_0\right) = P_{mT} - P_{eT} \quad (5)$$

Substituting $\ddot{\theta}_0$ in (5) from equation (2),

$$P_{ej} = P_{mj} - \left(P_{mT} - P_{eT}\right)M_j / M_T - M_j \ddot{\phi}_j \quad (6)$$

Neglecting oscillatory power transfers from one rotor to another resulting from synchronizing oscillations leads to the assumption that no generator rotor can be accelerating or decelerating relative to another during the time step of integration. It follows, therefore, that during this time; no rotor can be accelerating or decelerating relative to the system center of inertia. This means that any change that takes place in Φ_j during the time step of integration is assumed to occur at constant velocity. Hence $\ddot{\phi}_j$ in equation (6) can be set equal to zero. Therefore, generator j must be producing electrical power as given by the equation (7).

$$P_{ej} = P_{mj} - \left[P_{mT} - P_{eT}\right]\frac{M_j}{M_T} \quad (7)$$

The system equations of motion are given below:

$$\dot{\omega}_0 = \left(P_{mT} - P_{eT}\right)/M_T \quad (8)\ \dot{\theta}_0 = \left(\omega_0 - \omega_s\right) \quad (9)$$

and the governor turbine equations in the symbolic form,

$$\dot{P}_{mj} = F\left(P_{mj}, \omega_j\right) \quad (10)$$

Where j=1 to n

With the assumption that all speed governors respond to the system angular velocity ω_0, equation (10) can be rewritten as,

$$\dot{P}_{mj} = F\left(P_{mj}, \omega_0\right) \quad (11)$$

For most systems this approximation is adequate. At any instant of time, knowing P_{eT}, equations (8), (9), (11) can be integrated forward by one time step. From this the new values of ω_0, θ_o, and P_{mj} are known at (t+td). Only P_{eT} need to be calculated at (t+td) so as to take care of changes in network losses and load powers. At this stage an iterative procedure is adopted by using a power flow solution method to calculate new P_{eT} as described below.

II. GENERATOR REPRESENTATION

Generator representation has been simplified by eliminating damper windings and other sub-transient effects. Due to elimination of synchronizing oscillations, relative movement between the rotor and the air gap flux wave is not rapid enough nor of sufficient magnitude to induce significant currents in the damper windings. Hence the damper bar winding is not represented in the model. The field flux linkages are taken into account. With conventional d-q representation of the machine, only field winding is assumed to be on the d-axis results in the following equations.

$$E_q = V_T + (r_a + jx_q)I_T \quad (12)$$

$$E_I = E_q' + (x_d - x_d')I_d \quad (13)$$

$$E_q = E_q' + (x_q - x_d')I_d \quad (14)$$

$$\dot{E}_q' = (E_F - E_I)/T'_{d0} \quad (15)$$

III. EXCITATION SYSTEM

The excitation system is represented by IEEE type-I rotating exciter model. The field voltage, E_{FD}, is specified by excitation system equations. A simplified representation retaining only the exciter time constant, derivative feedback and exciter saturation can be written symbolically as

$$\dot{E}_F = F(E_F, |V_T|) \quad (16)$$

IV. ESTIMATION OF TOTAL ELECTRICAL POWER (P_{ET})

From the initial base case power flow conditions obtained prior to disturbance, E_q, E_I, E_q' are calculated using equations (12) to (14) respectively.

The initial field voltage E_F is set equal to E_I.

The equations (15) and (16) are integrated forward one time step for each generator and new values of E_I calculated from equation (13) set up the necessary constraint over the magnitude of the generator internal voltage E_q via equation (14). This together with the generator powers calculated from equation (7) is specified at all generator internal buses which are added to the network, except at the slack bus where angle and E_q are specified. These buses are treated as the voltage controlled buses.

The generator admittance, $1/(r_a+jx_q)$, becomes a branch of the network. The generator terminal buses

are treated as load buses with P and Q specified as zero. The loads can be represented in either ways, i.e. P-Q type or constant admittance type. In the D.E.B. model, the loads are represented as constant P-Q type. The diagonal elements of Y-matrix are modified accordingly to take into account the generator internal buses. All the necessary information is available to carry out a power flow solution. FDLF Method is used to compute P_{et} in the power-frequency transient simulation program.

Let the slack generator bus power from power flow solution be 'P_{slack}' which provides the power needed to balance total network input against loads plus losses. It indicates that the slack generator is not having the same acceleration as the other generations which is contrary to dynamic energy balance simulation procedure. However, the power flow solution provides a new value of P_{et} and this can be expressed as,

$$P_{eT}(new) = \sum_{\substack{j=1 \\ j \neq s}}^{n} P_{ej}(old) + P_{slack} \qquad (17)$$

Where s is the slack machine number.
Therefore new P_{ej} is given by

$$P_{ej}(new) = P_{ej}(old) + (P_{slack} - P_{es}) M_j / M_T \qquad (18)$$

Where j=1, 2, 3.....n
The equations (18) provide new generator powers which form the input to a new power flow solution. The iterative procedure between equations (18) and power flow solution is continued until (P_{slack}-P_{es}) <=ε, where ε is a specified tolerance. At this stage, the P_{et} at (t+dt) is correctly computed. Since all conditions at (t+dt) are known, the equations of motion of system center of inertia can be integrated forward one step so as to obtain new ω_0 and θ_0. All system dynamic equations are solved by using Euler's modified method.

V. ESTIMATION OF EACH GENERATOR ROTOR ANGULAR VELOCITY (Ω_J)

It should be noted that the rotor angular velocity, ω_0 appearing in the governor equations (11) (the angular velocity of the system center of inertia) is being used as the speed signal. This is an acceptable approximation in most systems but may produce some degradation in governor performance in weakly coupled systems where a redistribution of prime mover inputs during a power-frequency transient can cause large angle changes. The rate of these angles changes may be large enough to require calculations of individual generator angular velocities. It must be noted that this correction is made necessary, not by synchronizing oscillations, which have been eliminated from the dynamic energy balance, but by relative movement between rotors as system operating conditions change slowly in response to prime mover input variations. Successive power flow solutions provide the individual rotor speeds. Let generator's' be the slack machine and introduce $\rho_j = (\Phi_j - \Phi_s)$, where ρ_j is the angle of rotor j with respect to the slack generator rotor. These angles are known after the power flow solution is obtained and are the bus angles w.r.t the slack bus. The angles Φ and ρ are related by a linear transformation,

$$[\rho] = [c]\,[\Phi] \qquad (19)$$

Where,

$$[c] = \begin{bmatrix} M_1 + M_s & M_2 & \bullet & \bullet & M_n \\ M_1 & M_2 + M_s & \bullet & \bullet & M_n \\ \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet \\ M_1 & M_2 & \bullet & \bullet & M_n + M_s \end{bmatrix}$$

Row and column's' not included in [c]

$$[\rho] = \begin{bmatrix} \rho_1 \\ \rho_2 \\ \bullet \\ \bullet \\ \rho_n \end{bmatrix} \qquad [\phi] = \begin{bmatrix} \phi_1 \\ \phi_2 \\ \bullet \\ \bullet \\ \phi_n \end{bmatrix}$$

This means that the angle ρ calculated by the power flow can be transformed to angles measured with respect to center of inertia using,

$$[\Phi] = [c]^{-1}[\rho] \qquad (20)$$

The angular velocity of rotor j is determined from,

$$\omega_j = \dot{\phi}_j + \omega_0 \qquad (21)$$

Since it was assumed earlier that changes in Φ_j occur at a constant rate during the integration time step, equation (22) is a satisfactory estimate of Φ_j

$$\dot{\phi}_j(t+dt) = (\phi_j(t+dt) - \phi_j(t))/dt \qquad (22)$$

The values Φ_j(t+td) and Φ_j(t) are obtained by using equation (20) to transform the angles from successive power flow solutions. Rotor speed determined from equation (21) is a more accurate governor feedback signal than ω_0, but the simpler approach is adequate for most applications.

III. RESULTS

The simulation of power-frequency transients based on D.E.B model is being carried out on IEEE-14 bus test system.

The power-frequency transients are studied for disturbances of generation loss and load loss. For each class of problems, two sub-case studies are

being performed. In the first sub-case study, the angular velocity of system center of inertia ω_o is being used as the speed signal to the governors controlling the turbines of individual machines.
In the second sub-case study, actual angular velocities ω_j of the individual machine rotors are being estimated based on the transformation matrix (discussed in section 3.2) and are used as speed signals.

The results for both studies are shown in table (1) and (2). The variations of system frequency behaviour as a function of time for both cases are shown in the figure (1) and (2).

Table 1: Load 4 Trip case

Time(sec)	Frequency	
	ω_o is fed as speed signal	ω_j's is fed as speed signal
0	50	50
2	50.76772	50.76757
4	50.51595	50.52065
6	50.48248	50.48227
8	50.48496	50.48723
10	50.46447	50.46575
12	50.46465	50.46611
14	50.45917	50.46059
16	50.45694	50.45829
18	50.45434	50.45566
20	50.45214	50.45342
22	50.45007	50.45132
24	50.44811	50.44937
26	50.44628	50.44747
28	50.44454	50.4457
30	50.4429	50.44401

Table 1: Generator 3 Tripped

Time(sec)	Frequency	
	ω_o is fed as speed signal	ω_j is fed as speed signal
0	50	50
2	49.85744	49.85858
4	49.86675	49.86544
6	49.89635	49.89711
8	49.88854	49.88842
10	49.8925	49.89249
12	49.89288	49.89289
14	49.89288	49.89285
16	49.89307	49.89309
18	49.89315	49.89316
20	49.89315	49.89314
22	49.89316	49.89316
24	49.89316	49.89316
26	49.89316	49.89316
28	49.89316	49.89316
30	49.89316	49.89316

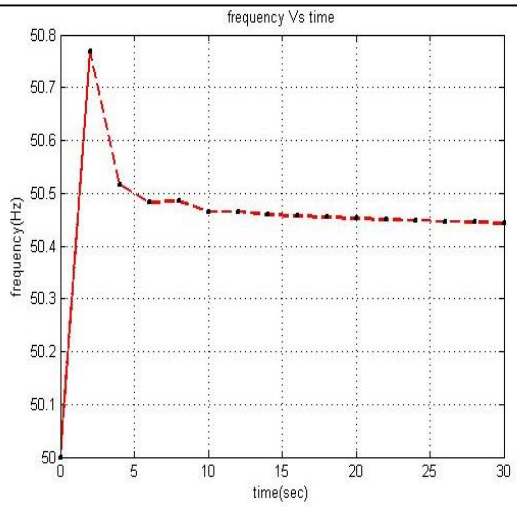


Figure 1: Load 4 trip case

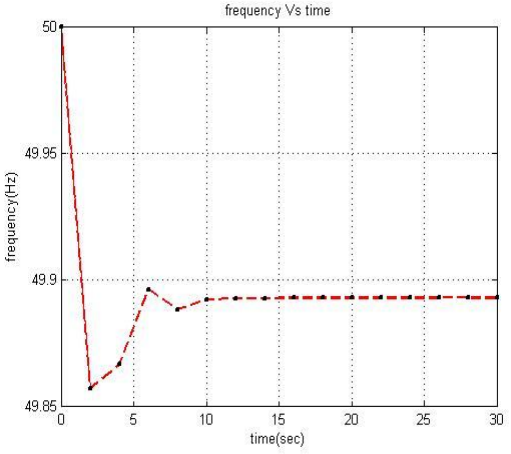


Figure 2: Generator 3 trip case

CONCLUSIONS

The D.E.B. model in the present form appears to be suitable for off-line studies. In the present study, the load behaviour due to frequency and bus voltage variations is not being considered. But, it is relevant to include the load modelling particularly from the point of view of power frequency behaviour in the D.E.B. model. The ward equivalents or similar type of equivalents for network representation can be incorporated in this model so as to minimize the computational burden. Security aspects like line flow constraints, bus voltage constraints etc could be taken into account to make the D.E.B. model an effective tool to study the power-frequency related aspects.

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