Transient Stability Assessment and Synchronization of Multimachine Power System Using Kuramoto Model

S.Sharma, S.Kulkarni, A.Maksud, S.R.Wagh, and N.M.Singh
Department of Electrical Engineering
Veermata Jijabai Technological Institute (V.J.T.I), Matunga Mumbai-400019, India
Email: sharma.shikha.jbp@gmail.com

***Abstract*—The crucial issue of loss of synchronization in post-disturbance conditions may lead to blackouts if corrective action is delayed. The complication increases due to large computation burden and time for wide-area network where thyristor-controlled series compensator (TCSC) is used as controller for transient stability enhancement. The trade-off in accuracy and speed in generating control law using linearized models becomes ineffective for changed operating scenarios. In addition, forming multi-machine linearized model becomes challenging when TCSC appears as non-separable element of a dense admittance matrix, which can be separated as a control variable in single-machine infinite-bus system. Overcoming the limitations of linearized controllers, the present paper verifies the Kuramoto mean-field condition using Kron reduction with non-trivial transfer conductances for unstable post-fault scenario. To regain synchronization effectively, necessary TCSC compensation has adjusted network parameters as proved by MATLAB simulations performed on 12-bus system, where real-time data is acquired by phasor measurement units.**
Keywords: Kuramoto model, PMU, Synchronization, Transient stability, TCSC .

I. Introduction

Stability is a major concern in the planning and operation of power systems. The recovery of a power system subjected to a severe large disturbance such as a short circuit in a transmission line, sudden loss of generation, overloading due to line flows, or the loss of a large load may cause instability. If such disturbances are not cleared rapidly, instability may ultimately lead to power failure, along with the economic losses associated with the occurrence of such events. Typically, the system must be designed and operated in such a way that a specified number of credible contingencies do not result in failure of quality and continuity of power supply to the loads. This calls for accurate calculation of the system dynamic behavior, which includes the electro-mechanical dynamic characteristics of the rotating machines, generator primary controls, compensators, loads, and other controls. Transient stability analysis can be used for dynamic analysis over time periods from few seconds to few minutes depending on the time constants of the dynamic phenomenon modeled. Transient stability assessment (TSA) is a part of dynamic security assessment of power systems which involves the evaluation of ability of a power system to maintain synchronism under severe but credible contingencies. Methods normally employed to assess TSA are by using time domain simulation [1] in which it is necessary to observe first swing stability and next successive swing oscillations, and line flows. Another way of tackling transient stability is a graphical method, popularized in the thirties, and called Equal-Area Criterion (EAC). This method deals with a one-machine system connected to an infinite bus and stability is analysed using the concept of energy [2], which removes the necessity of plotting swing curves by Time domain simulation (TDS).

In power system, synchronization issue is observed as the maintaining $w = w_s$ and $P_m = P_e$, which gives perfect power balance between generation and demand and system is stable. However, it is not known what margin is left and the dynamics of 80% load nodes in apriori. Consider a two area system, assuming generation in area 1 generation is 100 MW and load demand is 80 MW, in area 2 generation is 80 MW and demand is 100 MW. Perfect power balance between total generation and demand in system results in stable operation. Whenever there is a contingency in system which leads to outage of one tie line, to fulfil the demand of load in other area, whole power is transmitted through other line and overloading of tie line can cause outage and leads to the formation of two separate islands. Moreover mismatch in generation and demand in different island leads to power network failure. A recent failure in the Northern Eastern Western (NEW) grid of India is an example of grid failure due to tie line overloading. Therefore generator synchronism is not the only issue which decides the system integrity and stability, in addition, monitoring of tie line power is also equally important. Those who work on rotor angle stability skip to observe tie line power. To maintain synchronism, especially rotor angle stability, fault should be cleared at earliest possible before Critical Clearing Time (CCT). However, in short span of time, it is difficult in power system, which is a wide area network, results in inaccurate operation of grid. As a result, system is not able to survive with its own inertia and damper coefficients and there is need to call for controller. FACTS family provides controller for power system [3], which is characterise as series and shunt controller. Shunt compensator like Static VAR Compensators (SVC), STATic synchronous COMpensator (STATCOM) are effective for voltage stability, reactive power control, and power oscillations damping. Series compensator like Thyristor-Controlled Series Compensator

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(TCSC) [4] is useful for the power control. To control tie line power TCSC is the only option.

This paper is organised as follows, Section I represents the literature survey, followed by highlighting necessity of Kuramoto Mean Field Model (KMFM) for Power system in Section II. Section III discusses mathematical preliminary required for representation power system for applying KMFM, Section IV describes phase locking oscillators represented by Kuramoto Model. In Section V application of KMFM in power system is achieved which is validated through case study in Section VI, followed by conclusion drawn from the analysis in Section VII.

II. Necessity of KMFM for Power system

Mathematical representation of highly non-linear power system is quite complex. The detailed dynamics including rotor swing, rotor flux, exciter with saturation, and governor dynamics can be captured in a set of coupled nonlinear Differential-Algebraic-Equations (DAE). In addition, dynamics of TCSC is also important in control law. For Single Machine Infinite Bus (SMIB) representation of power system a successive linearization can be performed on this set of DAE which results into linearised model describing the detailed dynamics of the power system. The general form of which is:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{1}$$

where $x(t)$ is a state vector, A is the system matrix, B is the input matrix and $u(t)$ is the control input vector. With this model it is possible to design a linear or nonlinear controller and used for improvement of transient stability. However, linearization for Multi Machine Power System (MMPS) is more complex with TCSC controller [5]. TCSC reactance is not easily available as a control variable u in (1) for MMPS, since it becomes a non-seperable element of a higher order dense admittance matrix. In MMPS, for assessment, control and improvement of transient stability problem, TDS method is most popular but, it is highly time consuming and does not lead to real time controller.

In view of this, KMFM is found to be the most appropriate model to represent MMPS with series compensation which can be better understood using knowledge of graph theory. To control the system there are two methods node weight control by use of SVC, STATCOM and edge-weight control by using TCSC. This paper presents the analysis and improvement of transient stability of a MMPS by edge-weight control of Network-Reduced Model (NRM). To control overloading in tie line TCSC is used as controller in the transmission line during post-disturbance. Control law for the TCSC is based on the speed deviation of the generator which is formulated in terms of the coupling coefficient of KMFM.

III. Mathematics preliminaries for Representation of power system

A. Representation of power system using Graph Theory

From the graph topology point of view the power system network can be modelled as network-preserving model (NPM) and NRM. In order to model a power system network using graph theory, it is necessary to understand the terminology of graph theory. An undirected graph G consists of n-dimensional vertex set, V, and an e-dimensional edge set E, where an edge is an unordered pair of distinct vertices in G. A vertex v_i is said to be a neighbour of another vertex v_j if they are connected by an edge. A graph is said to be strongly connected if any two pairs of vertices can be connected by a walk [5].

- A weighted graph is a graph (V, E) together with a map $\varphi : E \rightarrow R$ that assigns a real number $w_{ij} = \varphi(e_{ij})$ called a weight to an edge $e_{ij} = (v_i, v_j) \in E$.
- The set of all weights associated with E is denoted by W.
- A weighed graph can be represented as a triplet $G = (V, E, W)$.

Matrices associated with a graph are:

- The adjacency matrix $A = [a_{ij}] \in R^{n\times n}$ of a graph G of order n is given by

$$a_{ij} = \begin{cases} 1 & (v_i, v_j) \in E \\ 0 & otherwise \end{cases}$$

- The degree matrix of a graph is a diagonal $n \times n, (n = |V|)$ matrix $\triangle = diag(deg_{out}(V_i))$ with diagonal elements equal to the out-degree of each node and zero everywhere else.

An orientation of a graph G is the assignment of a direction to each edge, so that the edge (i, j) is now an arc from vertex i to vertex j. The graph G with orientation σ is denoted by G^σ. The incidence matrix $B(G^\sigma)$ of an oriented graph G^σ is the $(n \times e)$ matrix whose rows and columns are indexed by the vertices and edges of G, respectively, such that the (i, j) of $B(G^\sigma)$ is equal to 1 if the edge j is incoming to vertex i, -1 if edge j is outgoing from vertex i, and 0 otherwise. The symmetric matrix defined as:

$$L(G) = D(G) - A(G) = B(G^\sigma)B(G^\sigma)^T \tag{2}$$

is called the Laplacian of G and is independent of the choice of orientation σ. The Laplacian has several important properties such as:

- L is always positive semidefinite with a zero eigenvalue
- The algebraic multiplicity of its zero eigenvalue is equal to the number of connected components in the graph.

A positive number w_i associated to each edge forming a diagonal matrix $W := diag(w_i)$, results in weighted Laplacian matrix $L_w(G)$ as :

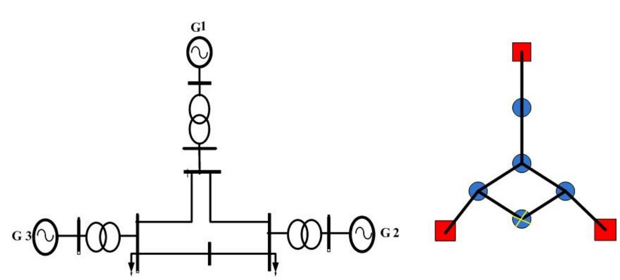

Fig. 1. Network-preserving model of power grid

$$L_w(G) = B(G^\sigma)WB(G^\sigma)^T \tag{3}$$

Using graph theory basics, power system is modelled as NPM shown in Fig.1.

Analysis of Kuramoto model of coupled non-linear oscillators is based on all-to-all connectivity of oscillators. When transient stability problem in MMPS is handled as a special case of more general synchronization problem using KMFM model, all-to-all connectivity among generators is achieved by Kron reduction.

B. Representation of power system after Kron Reduction

A common assumption in power system is that loads are modelled as passive admittances and these passive nodes of power network can be eliminated by Kron reduction. The original electrical network is replaced with a simpler network (in the sense of number of nodes) that still provides same relationships between voltages and currents at the terminals of the synchronous generators. For any matrix $M \in C^{n\times n}$, element in the i^{th} row and j^{th} column of M is denoted by M_{ij} partitioned as:

$$M = \begin{bmatrix} M_1 & M_2 \\ M_3 & M_L \end{bmatrix}$$

The matrix ($M_1 - M_2 M_L^{-1} M_3$) is called the Schur complement of M_L in M. If set (V_b, V_i) is the partition of V such that V_b is a set of boundary nodes and V_i is the set of internal nodes. B_b is the matrix obtained from B by eliminating rows corresponding to vertices not in V_b. The Schur complement of the matrix $B_b G B_b^T$ in the weighted Laplacian $B(G^\sigma)WB(G^\sigma)^T$ of graph G is called the Kron Reduction matrix of graph G with respect to set of vertices V_b. Procedure of Kron reduction can be better understood from Fig.2

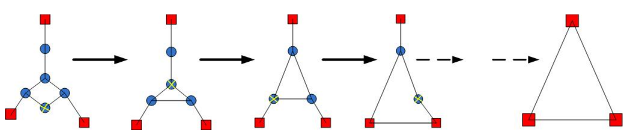

Fig. 2. Network-reduced model of power grid

IV. Phase Locking Oscillators: Kuramoto Model

The dynamics of a set of N coupled oscillators with states θ_i , coupling strength K, and natural frequency w_i is described by Kuramoto model as [6]:

$$\dot{\theta}_i = \omega_i - \sum_{j=1}^{n} K_{ij} sin(\theta_i - \theta_j) \tag{4}$$

Coupling strength is an important parameter which acts as an indicator of synchronization. When the coupling is weak, oscillators run incoherently with their natural frequencies, whereas, coupling strength beyond a certain critical value for which all phase differences remain constant, results in phase locking of the oscillators and synchronization is achieved. A different interpretation of synchronization can be thought of in terms of order parameter, r. Assuming N oscillators as points on a circle moving with different angular velocities, under complete synchronization all the points move around the circle in synchrony. The order parameter of the centroid of the points as a natural measure of synchronization which is defined as

$$r(t)e^{(i\phi(t))} = \frac{1}{N}\sum_{j=1}^{n} e^{(i\theta_j(t))} \tag{5}$$

where $r(t)$ measures phase coherence of the oscillators and $\phi(t)$ measures the average phase. Kuramoto model represented in terms of order parameter as :

$$\dot{\theta}_i = \omega_i - Krsin(\phi_i - \theta_i) \tag{6}$$

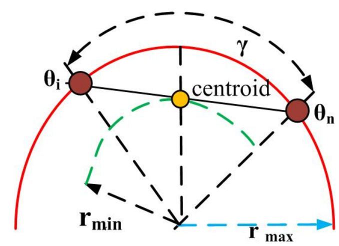

Fig. 3. Order parameter representation of oscillators

As $K \rightarrow 0$, oscillators oscillates with their own natural frequencies resulting in, $r \rightarrow 0$, as $t \rightarrow \infty$ implying incoherent oscillators. When $K \rightarrow \infty$, the oscillators are synchronized to their mean phase indicated by $r \rightarrow 1$. For $0 < r < 1$, some of the oscillators are rotating out of synchrony with the locked oscillators. Thus, synchronization in the KMFM is revealed by non-zero value of order parameter.

Using the graph terminology, Kuramoto model of any general interconnection topology can be represented as

$$\dot{\theta}_i = \omega_i - \frac{K}{N} B sin(B^T\theta) \tag{7}$$

where, B is the incidence matrix of an arbitrary orientation of the unweighted graph,

N number of oscillators,

θ and ω are $N \times 1$ vectors, and

$\phi = B^T\theta$ is e-dimensional vector of phase differences.

This model is more useful in analysing the system, particularly when system topology is changing.

V. Power system represented by Kuramoto model

The detailed dynamic model of a MMPS, which includes rotor swings, rotor flux, exciter with saturation, and governor dynamics, can be captured in a set of coupled nonlinear DAE model. Modeling the complete set to characterize the whole system represents a tantalizing effort. KMFM for MMPS with non-trivial transfer conductances [7], in remotely situated generators that are coupled through power flow. Posing synchronization problem as a special case of transient stability problem, second order non-uniform Kuramoto model for power system derived from swing equation:

$$\dot{\omega} = \frac{2H}{\omega_{ref}}(P_m - P_e - P_D(\omega - \omega_{ref})) \tag{8}$$

can be written as:

$$\frac{M_i}{\pi f_0}\ddot{\delta}_i = P_{mi} - E_i^2 G_{ii} - D_i\dot{\delta}_i - P_{ei}, \quad for\ i \in \{1, \cdots, n\} \quad (9)$$

where P_{ei} is:

$$P_{ei} = \sum_{j=1}^{n} |E_i||E_j|[Re(Y_{ij})cos(\delta_i - \delta_j) + Im(Y_{ij})sin(\delta_i - \delta_j)] \quad (10)$$

Defining effective power input to generator i as: ω_i :=$(P_{mi} - E_i^2(G_{ii}))$, coupling weights represented by power transferred between generator i and j is $P_{ij} = |E_i||E_j|Y_{ij}|$ with $P_{ii} = 0$, (9) can also be written as:

$$\frac{M_i}{\pi f_0}\ddot{\delta}_i = D_i\dot{\delta}_i + \omega_i - \sum_{j=1}^{n} P_{ij}sin(\delta_i - \delta_j + \varphi_{ij}) \quad (11)$$

To remove fast modes from a higher order dynamics which is a combination of fast and slow modes, singular perturbation is applied to (11). This is achieved by making parameter $\in = \frac{M_{max}}{\pi f_0 D_{min}}$ very small.

The resulting network reduced model power system dynamics is:

$$D_i\dot{\delta}_i = \omega_i - \sum_{j=1}^{n} P_{ij}sin(\delta_i - \delta_j + \varphi_{ij}) \quad (12)$$

which is similar to (4). As the swing equation is restricted to only generator nodes, there is the need of NRM, which is achieved using Kron reduction as discussed in Section III.

The necessary condition for synchronization is given by

$$\Gamma_{min} \geq \Gamma_{critical} \quad (13)$$

where,

$$\Gamma_{min} = n \min_{i \neq j}\left(\frac{P_{ij}}{D_i}cos(\varphi_{ij})\right) \quad (14)$$

and $\Gamma_{critical}$ which consists of two components, namely,

$$\Gamma_{crit1} = \max_{i \neq j}\left|\frac{\omega_i}{D_i} - \frac{\omega_j}{D_j}\right| \quad (15)$$

and

$$\Gamma_{crit2} = 2 \max_{i \in 1, \cdots, n} \sum_{j=1}^{n}\left(\frac{P_{ij}}{D_i}sin(\varphi_{ij})\right) \quad (16)$$

$$\Gamma_{critical} = \frac{1}{cos(\varphi_{max})}(\Gamma_{crit1} + \Gamma_{crit2}) \quad (17)$$

To assure synchronization in power grid derivative of function representing system dynamics should be a non-increasing function. As function defined for assuring synchronization is a non-smooth function, Dini derivative of the function along the dynamical system should be calculated as:

$$D^{+}V(\delta(t)) = \dot{\delta_m} - \dot{\delta}_l \leq 0 \quad (18)$$

where function is define as

$$V(\delta) = max(|\delta_i - \delta_j|)| \quad i, j \in 1, \cdots, n) \quad (19)$$

By substituting the value in (18) from (12), condition (13) is derived.

Although, Kron reduction simplifies the power network by merging load nodes in the generator nodes, thereby giving all-to-all connectivity between the generators, some of the tie lines are not directly available for line flow calculations. To overcome this problem, original NPM can be represented by incidence matrix B of order $(n + m) \times e$ (with n generator nodes and m load nodes) corresponding to $n + m$ nodes and e edges of the underlying graph G with arbitrary orientation. In matrix form (12) can be rewritten as

$$\dot{\delta} = \omega - PBsin(B^T\delta) \quad (20)$$

where P is $e \times e$ power flow matrix. This generalization is useful if the topology of the system under consideration is changing from pre-fault to post-fault. Condition for synchronization in the NPM from (13) is:

$$K_c > PB_{pre}Bsin(B^T\delta) \quad (21)$$

which is obtained from

$$B_{pre}\dot{\delta} = B_{pre}(\omega - PBsin(B^T\delta)) \quad (22)$$

where B_{pre} is the pre-multiplying row matrix with dimensions $1 \times (n + m)$. Depending upon position of δ_m and δ_l in angle array, elements of B_{pre} are $+1$ and -1 respectively, remaining elements being 0.

When the condition for synchronization given by (13) is not fulfilled such as during fault in the power network then to bring the system in synchronism, a TCSC module acting as a variable reactance is used as a controller.

The TCSC consists of three main components: capacitor bank C, bypass inductor L and bidirectional thyristors SCR [3]. The firing angles of the thyristors are controlled to adjust the TCSC reactance in accordance with a system control algorithm, normally in response to some system parameter variations. According to the variation of the thyristor firing angle or conduction angle, this process can be modeled as a fast switch between corresponding reactance offered to the power system.

The TCSC can be controlled to work either in the capacitive or the inductive zones avoiding steady state resonance. This mode is called venire control mode. There exists a steady-state relationship between the firing angle α and the reactance X_{tcsc} [8] . This relationship can be described as

$$X_{tcsc}(\alpha) = X_C - X(\sigma) + X(\beta) \quad (23)$$

where,

$$X(\sigma) = \frac{X_C^2}{X_C - X_P}.\frac{\sigma + sin\sigma}{\pi} \quad (24)$$

$$X(\beta) = 4\frac{X_C^2}{X_C - X_P}\frac{cos^2(\frac{\sigma}{2})}{K_T^2 - 1}\frac{K_T tan(\frac{K_T\sigma}{2}) - tan(\frac{\sigma}{2})}{\pi} \quad (25)$$

X_C = Nominal reactance of the fixed capacitor C.

X_P = Inductive reactance of inductor L connected in parallel with C.

σ = $2(\pi - \alpha)$ = Conduction angle of TCSC controller.

K_T = $\sqrt{\frac{X_C}{X_P}}$ = Compensation ratio

The Model of the TCSC controller is [3]. After a disturbance, oscillations are reflected in the deviations in the generator rotor angle ($\Delta\delta$), rotor speed ($\Delta\omega$) and accelerating power (ΔP_a). In this study, the input signal of the proposed

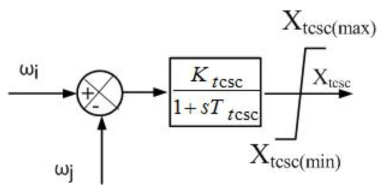

Fig. 4. Model of TCSC controller

TCSC controller is the speed deviation $\Delta\omega$ and the output is the TCSC reactance ($X_{tcsc}(\alpha)$) required to minimize the power system oscillations so as to improve the stability and corresponding firing angle α of the thyristor is calculated from (23).

VI. Case Study on MMPS

A. Representative MMPS

The 4-generator, 12-node system [9] as shown in Fig.6, is adopted in the study for the purpose of illustrating the performance of the KMFM developed for MMPS in Section V, and investigating the feasibility of its implementation. The system has two TCSCs - TCSC1 in line L_{10} between nodes N_5 and N_7, and TCSC2 in transmission line L_7 between nodes N_6 and N_8. The TCSC1 is actively used for providing series compensation. If compensation due to TCSC1 is not sufficient, a provision has been made to activate TCSC2. The operating constraints of a TCSC are associated with its reactance and can be expressed in terms of the following inequalities:

$$X_{tcscmin} \leq X_{tcsc} \leq X_{tcscmax}$$

$X_{tcscmin}$ and $X_{tcscmax}$ are the minimum (capacitive) and maximum (inductive) limits of TCSC reactance respectively.

A real time data required to activate TCSC can be obtained from PMUs located at different places in the WAN. Optimal placement of PMUs [10],[11] based on complete observability requires four PMUs at the generator buses. However, due to insertion of TCSC at nodes N_5 and N_6, for acquiring real-time data required for deriving necessary control law, needs two additional PMUs at two nodes of active TCSC. Even though the number of PMUs used are more than the optimal placement calculation it will be useful in giving better observability under (n-1) contingency.

B. Simulation results and analysis

1) Verification of system performance without controller: A 3-phase dead-short fault is considered at various location in the power system for which by performing continuous repeated TDS, CCT is found. If the fault is cleared beyond CCT, system is unstable. Considering fault on line L_5, near node N_{12} at 0.5s. It can be seen from the relative rotor angle plot in Fig.7 that power system network gets separated in two

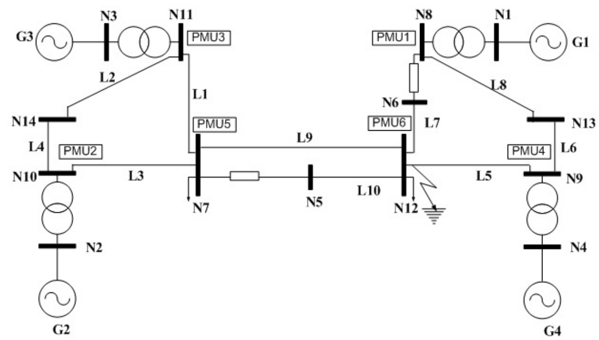

Fig. 5. Representative MMPS with TCSC

parts generator 4 form one group or island, while remaining generators (i.e. 2, 3) form second group.

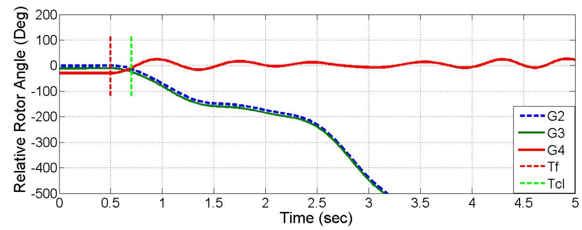

Fig. 6. Variation of rotor angle delta without controller

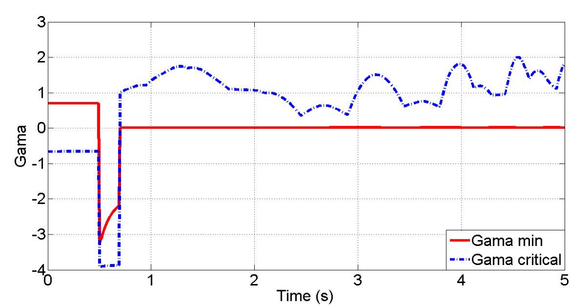

Fig. 7. Variatin of Kuramoto coefficients for unstable system

From transient stability response it can be observed that the machines in the given group remain in synchronism with each other inside the group. However, the first group of machine seems to fall out of synchronism with the second group of machines. The separation of groups increases as time passes, indicating that unless corrective action is taken as early as possible, recovering the system stability may become very difficult or in some cases, even impossible. The unstability which is observed in rotor angle can be conformed by proposed Kuramoto condition and shown in Fig.8 where it can be observed that before fault, condition $\Gamma_{min} > \Gamma_{critical}$, is satisfied, during fault condition is violated, in post fault condition $\Gamma_{min} > \Gamma_{critical}$ is not satisfied indicating system is unstable. However, system can be stabilized by firing the TCSC and injecting the necessary compensation results of which is given in next section.

2) Verification of system performance with controller: Depending on the speed deviation with respect to time, the necessary TCSC reactance required for regaining stability is given by the controller and corresponding firing angle can be obtain using (23). By firing the TCSC to its corresponding value system regains its stability which is depicted in Fig.9 and also conformed from Kuramoto condition in Fig.10. Based on

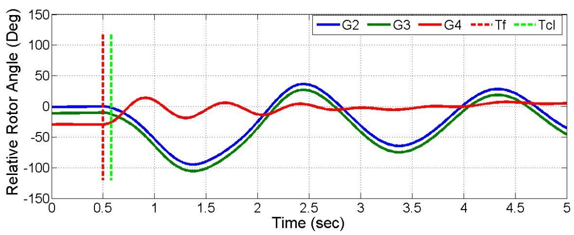

Fig. 8. Variation of rotor angle delta with controller

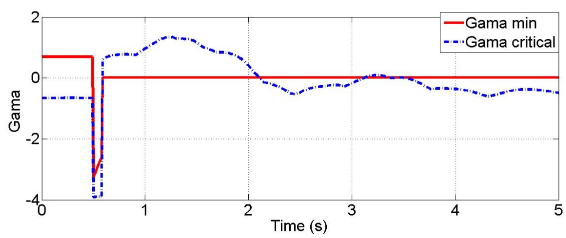

Fig. 9. Variation of Kuramoto coefficients for synchronized system

the system dynamics, for a given case study, it is found that the third swing of rotor angle is having slightly higher peak value as compared to second swing. However, such slow dynamics are also taken care of by the KMFM coefficient calculation and the required TCSC compensation is modified to maintain synchronism.

TABLE I
FIRING ANGLE FOR FAULT LOCATION NEAR NODE 12, AT LINE 5

Clearing Time	TCSC Inserted	Firing Angle
Upto 0.19 Sec	0%	0^0
0.195 -0.22 Sec	20%	125.52^0
0.23 -0.24 Sec	40%	125.47^0
0.25 - 0.26 Sec	60%	100.51^0
0.27 - 0.29 Sec	80%	92.86^0

TABLE II
FIRING ANGLE FOR FAULT LOCATION NEAR NODE 9, AT LINE 5

Clearing Time	TCSC Inserted	Firing Angle
Upto 0.18 Sec	0%	0^0
0.19 -0.21 Sec	20%	125.52^0
0.22 -0.24 Sec	40%	125.47^0
0.25 - 0.26 Sec	60%	100.51^0
0.27 - 0.28 Sec	80%	92.86^0

For various fault location and clearing time, corresponding values of TCSC reactance and firing angles are tabulated. From

TABLE III
FIRING ANGLE FOR FAULT LOCATION NEAR NODE 11, AT LINE 2

Clearing Time	TCSC Inserted	Firing Angle
Upto 0.1 Sec	0%	0^0
0.10 -0.12 Sec	20%	125.52^0
0.13 -0.14 Sec	40%	125.47^0
0.15 - 0.17 Sec	60%	100.51^0
0.17 - 0.2 Sec	80%	92.86^0

the Tables it can be seen that if the fault location is nearer to the location of TCSC, then from available TCSC time margin for clearing fault and regaining the stability is comparatively larger than if the fault location is farther from TCSC location.

VII. CONCLUSION

Considering the importance of maintaining real-time Transient stability and its related issues, especially with WAN, having large multi machine networks, the paper has proposed very effective tool of stability assessment in terms of KMFM which is verified on a representative MMPS by carrying out MATLAB simulations. Necessary series compensation can be provided to satisfy synchronization condition using real time data acquired from PMU. The method gives an edge over traditional TDS methods by minimizing computation burden and time which is the necessity of real time controllers. The idea can be further explored for distributed control strategy for adaptive controller coordination schemes.

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