An Efficient Multi-area Networks-Merging Model for Power System Online Dynamic Modeling

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***Abstract*—To improve accuracy and efficiency in power systems dynamic modeling, the distributed online modeling approach is a good option. In this approach, the power system is divided into sub-grids, and the dynamic models of the sub-grids are built independently within the distributed modeling system. The sub-grid models are subsequently merged, after which the dynamic model of the whole power system is finally constructed online. The merging of the networks plays an important role in the distributed online dynamic modeling of power systems. An efficient multi-area networks-merging model that can rapidly match the boundary power flow is proposed in this paper. The iterations of the boundary matching during network merging are eliminated due to the introduction of the merging model, and the dynamic models of the sub-grid can be directly "plugged in" with each other. The results of the calculations performed in a real power system demonstrate the accuracy of the integrated model under both steady and transient states.**

***Index Terms*—Boundary matching, distributed online modeling, dynamic modeling, multi-area networks merging model, power system.**

I. INTRODUCTION

DYNAMIC simulation is essential for power system dynamic security analysis and control, and the credibility of simulation results depends heavily on the precision of power system models and their parameters. However, modern power systems are complex, time-variant, and stochastic, and thus the system model and parameters used for dynamic simulation are not necessarily consistent with the actual power system [1]. Studies have shown that online modeling offers a solution to the aforementioned problem [1]–[4] in that it can match its models and parameters to the complex variations in power system operations.

To date, centralized modeling has been the traditional method used for power system modeling in which all of the power system components are modelled in the control center. However, in recent decades, the power grid has expanded exponentially, and the modern power system contains a large number of elements and nodes. To build a dynamic model of the whole system, therefore, is difficult and inefficient using traditional centralized modeling methods for such a wide area system [5]–[7]. In this context, the distributed online modeling of power system has received considerable attention [2], [8]. The whole power system is divided into several sub-grids, and the sub-grids are modelled independently in the distributed modeling center. The local disturbances, which occur frequently and only affect the components in a local-area power system, are then fully utilized to build the dynamic model of the sub-grids.

Many distributed modeling approaches have been proposed in past literature. A time-varying current injection based distributed modeling method is proposed in [9] to build the dynamic models of the sub-grids. In [10], an online parameter identification method with two-level architecture is developed. The measurement based online parameter identification is implemented at the substation level, and the identified parameters are validated in the control center.

Distributed steady-state modeling methods have also been studied [11]–[13]. In [12], [13], for example, a two-level linear state estimator is introduced. The data processing and the state estimation are distributed at the substations and at the control center, respectively. The bad data detection identification is carried out at the substation level, and the linear state estimator is performed at the control center level. Once the dynamic sub-grid models are built, they are then merged to construct a dynamic model of the whole system.

Direct merging of the sub-grid models, however, does not take place due to the power flow mismatch between the borders of different sub-grids. Under these conditions, boundary matching and network merging play an important role in distributed online dynamic modeling of power systems, primarily because a large number of sub-grid models are needed in order to merge online.

Boundary matching is usually used to attach the external network model to the internal model and build a steady state model for the whole system [14]–[17]. This requires that the part on the external network steady-state modeling must not affect the results of the internal state estimation, i.e., the power

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flow of internal network must remain unchanged after the networks merge. Multiple load flow and quasi-steady-state sensitivity [18] based methods have been proposed in [19] to match the boundary power flow, and the accuracy of the integrated model is satisfactory.

In this study, the outline of a distributed online dynamic modeling method for power system is proposed for the first time. A novel multi-area networks-merging model that rapidly matches the boundary power flow is introduced as a means to merge the dynamic models of the sub-grids; the new method then allows for the dynamic models of the sub-grid to be "plugged in" with each other directly. The proposed merging model and the existing sensitivity based methods are both applied in a real power grid with more than 2000 nodes. Steady and dynamic simulations are performed with comparative results verifying the effectiveness of the proposed model.

II. DISTRIBUTED ONLINE DYNAMIC MODELING OF A POWER SYSTEM

The scheme of the distributed online dynamic modeling method is shown in Fig. 1. In this method, the whole system is first divided into several sub-grids based on their distribution. Then, the dynamic models of the transmission network and the distribution network in each sub-grid with relatively small scale are built independently at the distributed modeling center, using the data of local disturbances measured by wide area measurement system (WAMS) and the local system-wide modeling method [9], [20]. Finally, the models of the transmission network and the distribution network in each sub-grid are merged with each other using the merging model, according to its network topology. Based on this, the models of the sub-grids are then constructed. The model of the whole system similarly is constructed via the network merging of all sub-grid models.

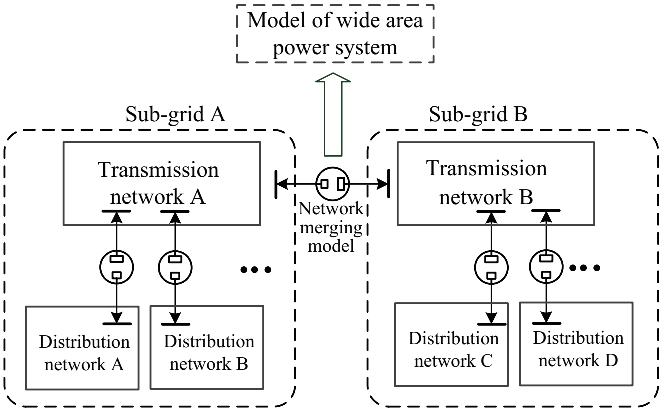

Fig. 1. Schematic diagram of the distributed online dynamic modeling for power system.

While power system dynamic modeling efficiency can be significantly improved with distributed sub-grid modeling processes at different modeling centers, there is a need for more sub-grid models to be merged, and thereby, a more efficient network merging method to be developed. In this study, we propose an efficient multi-area networks-merging model that can rapidly match the boundary power flow, which represents the most critical element in improving distributed online modeling performance. The traditional sensitivity based method for boundary matching is also performed for comparison.

III. POWER FLOW MISMATCHES BETWEEN BORDERS OF DIFFERENT SUB-GRIDS

The boundary power flows between sub-grids do not match because sub-grid modeling procedures are performed at different times. If we assume that the boundary power flow of a certain sub-grid is the exact value, then the power flow mismatches between the borders of different sub-grids can be easily obtained. A schematic diagram of boundary power flow is shown in Fig. 2. P_{A}, Q_{A}, U_{A}, θ_{A}, P_{B}, Q_{B}, U_{B}, and θ_{B} denote active power, reactive power, voltage magnitude, and voltage phase angle of the boundary buses in sub-grids A and B, respectively.

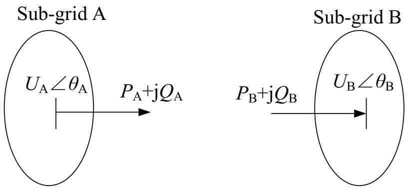

Fig. 2. Schematic diagram of boundary power flow.

Similarly, if we assume the boundary power flow of sub-grid B is exact, then the mismatches are given by

$$\Delta\theta = \theta_{\mathrm{A}} - \theta_{\mathrm{B}} \tag{1}$$

$$\Delta U = U_{\mathrm{A}}/U_{\mathrm{B}} \tag{2}$$

$$\Delta P = P_{\mathrm{A}} - P_{\mathrm{B}} \tag{3}$$

$$\Delta Q = Q_{\mathrm{A}} - Q_{\mathrm{B}} \tag{4}$$

where ΔU is the voltage magnitude mismatch, $\Delta\theta$ is the voltage phase angle mismatch, and ΔP and ΔQ are the active power and reactive power mismatches, respectively.

IV. SENSITIVITY BASED BOUNDARY MATCHING METHOD

To keep the power flow of the sub-grid B unchanged after the networks merge, the basic principles of the sensitivity based boundary matching method [19] are as follows: 1) The voltage phase and reactive power of the boundary buses in sub-grid A are set as the exact values in sub-grid B, i.e., $\theta_{\mathrm{A}} = \theta_{\mathrm{B}}$, $Q_{\mathrm{A}} = Q_{\mathrm{B}}$. 2) Some internal buses in sub-grid A are selected as the adjustable nodes. The voltage magnitude and the active power of the adjustable nodes in sub-grid A are then alternately adjusted to reduce ΔU and ΔP to zero based on the quasi-steady-state sensitivity.

Suppose that the number of the boundary buses is S, the active power mismatch is $\Delta\boldsymbol{P}_S$, the number of the adjustable nodes is M, and the total adjustable capacity is $\Delta\boldsymbol{P}_M$. The proper $\Delta\boldsymbol{P}_M$ should be solved to reduce $\Delta\boldsymbol{P}_S$ to zero. The relationship between $\Delta\boldsymbol{P}_M$ and $\Delta\boldsymbol{P}_S$ can be written as

$$\Delta\boldsymbol{P}_S = -\boldsymbol{B}_{SM}\Delta\boldsymbol{P}_M \tag{5}$$

where $\boldsymbol{B}_{SM}$ is the sensitivity matrix, the solution procedure can be found in [18].

Considering (5), $\Delta \boldsymbol{P}_M$ can be calculated as

$$\Delta \boldsymbol{P}_M = -\boldsymbol{B}_{SM}^T (\boldsymbol{B}_{SM} \boldsymbol{B}_{SM}^T)^{-1} \Delta \boldsymbol{P}_S. \tag{6}$$

The matching procedure of voltage magnitude is similar to that of active power. Note that the alternating iterations are necessary for the sensitivity-based method. Thus, a “plug and play” merging model is proposed to improve the efficiency of network merging.

V. Multi-area Networks Merging Model

To improve the accuracy and efficiency of the distributed online modeling of the power system, the following aspects should be considered for network merging: 1) In order to build the model of the whole system online, the power flow difference between the sub-grids should be matched rapidly and be less time-consuming. 2) After networks are merged, then the integrated model should accurately represent the system dynamics.

To address the first issue, the boundary mismatches can be directly compensated by adding a number of “virtual” electrical components between the boundary buses of different sub-grids where the iterations are eliminated. For instance, a “virtual” transformer can be added to compensate the mismatch of voltage magnitude ΔU by setting the appropriate transformation ratio. And a “virtual” phase shifter can be added to compensate the mismatch of the voltage phase angle.

For the second issue, in order to satisfy the accuracy of the integrated model under transient state, the fewest possible “virtual” components will be the preferred choice, and no dynamic elements should be included. For instance, the transformer and phase shifter are both static elements. And shunt admittance rather than the generator can be used to match the active and reactive power.

It should be noted that network topology is changed by the artificial addition of “virtual” components. However, such change is feasible and effective if the accuracy of the integrated model is satisfied under both the steady and transient states. For the sensitivity-based method, despite the fact that the network topology is unchanged, the results of networks merging may be inconsistent with the actual power flow because the power injections of adjustable nodes are tuned in an assumed manner.

Accordingly, as shown in Fig. 3, the merging model is a Γ-circuit consisting of the phase shifter, transformer, and admittance. The boundary nodes of sub-grids A and B are connected via the merging model so that the boundary power flow can be rapidly matched. In the proposed model, the shunt admittance $G + \mathrm{j}B$ rather than the constant power load is used to compensate for the active and reactive power mismatches ΔP and ΔQ because the active and reactive power of the power load keep constant under the transient state, i.e., the constant power load cannot reflect the variations of the active and reactive power under the transient state. The transformer and phase shifter are used to compensate ΔU and $\Delta\theta$, respectively. X_1, X_2, and X_3 are the transformer reactance, phase shifter reactance, and compensating reactance, respectively, where, X_1, X_2 are very small, and $X_1 + X_2 + X_3 = 0$.

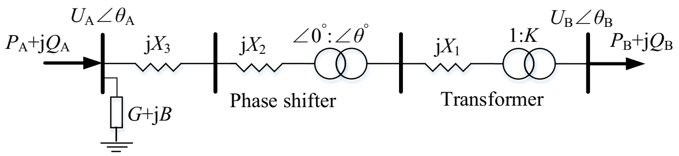

Fig. 3. Configuration of the network merging model.

The phase-shifting angle θ is directly set as the phase angle mismatch $\Delta\theta$

$$\theta = -\Delta\theta = \theta_{\mathrm{B}} - \theta_{\mathrm{A}}. \tag{7}$$

The transformer ratio K is set as

$$K = 1/\Delta U = U_{\mathrm{B}}/U_{\mathrm{A}}. \tag{8}$$

The relationship between $Y = G + \mathrm{j}B$ and the power mismatch can be written as

$$\Delta\bar{S} = \Delta P + \mathrm{j}\Delta Q = U_{\mathrm{A}}^2 Y^* = U_{\mathrm{A}}^2 (G - \mathrm{j}B) \tag{9}$$

where $\Delta\bar{S}$ is the complex power mismatch.

Then, $Y = G + \mathrm{j}B$ can be given by

$$\begin{aligned} Y &= G + \mathrm{j}B = \Delta P - \mathrm{j}\Delta Q / U_{\mathrm{A}}^2 \\ &= (P_{\mathrm{A}} - P_{\mathrm{B}}) - \mathrm{j}(Q_{\mathrm{A}} - Q_{\mathrm{B}})/U_{\mathrm{A}}^2 \end{aligned} \tag{10}$$

where G is negative if $P_{\mathrm{A}} < P_{\mathrm{B}}$, and B is negative if $Q_{\mathrm{A}} > Q_{\mathrm{B}}$.

To weaken the influence of the merging model on system dynamics, the values of X_1, X_2, and X_3 should be set as small as possible. In this study, $X_1 = X_2 = 0.0001$ p.u. and $X_3 = -0.0002$ p.u.

VI. Practical Application in a Provincial Power Grid

The distributed online modeling approach has been performed in a provincial power grid in China. To verify the feasibility of the proposed method, both the merging model and the sensitivity-based method are applied to integrate the models of the provincial transmission network (external network) and the regional distribution network (internal network). The steady states and dynamic responses of the integrated model are compared.

A. Topology and Initial State of the Provincial Power Grid

The topology of the provincial power grid is shown in Fig. 4, and the system scales of the external network and internal network are shown in Table I. Three substations connect the internal network with the external network. The 500 kV bus in substation A, the 220 kV bus in substation B, and the 220 kV bus in substation C are chosen as the boundary nodes. The initial states of the boundary nodes in the internal and external networks are shown in Table II. The initial boundary mismatches are quite large, particularly the phase angle mismatches, which reach up to 20°.

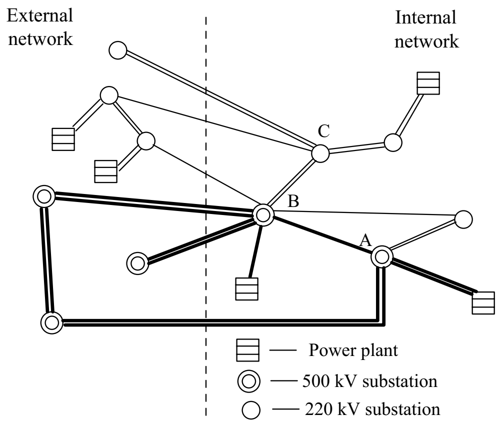

Fig. 4. Schematic diagram of the network topology.

TABLE I
NETWORK SCALE

Area	Total Number of Buses	Total Number of AC Lines	Total Number of Transformers	Total Number of Generators	Total Number of Loads
External network	2096	1225	1653	159	952
Internal network	312	384	251	3	87

TABLE II
INITIAL STATES OF THE BOUNDARY NODES

Boundary Nodes	Area	Voltage Magnitude (p.u.)	Voltage Phase Angle (°)	Active Power (p.u.)	Reactive Power (p.u.)
500 kV bus in substation A	Internal	0.98694	21.8811	9.79558	1.16632
	External	0.99141	−2.2429	8.75169	2.55094
220 kV bus in substation B	Internal	0.97084	16.6007	9.31804	2.79947
	External	0.99891	−6.1171	7.17623	0.42282
220 kV bus in substation C	Internal	0.96570	13.7593	−1.21999	−0.57253
	External	0.99096	−7.9396	−2.23954	−0.55611

TABLE III
PARAMETERS OF THE MERGING MODEL

Boundary Nodes	θ (°)	K	$G + jB$ (p.u.)
500 kV bus in substation A	24.12	0.995	$-1.062 - j1.409$
220 kV bus in substation B	22.72	0.972	$-2.146 + j2.38185$
220 kV bus in substation C	21.7	0.975	$-1.038 - j0.01671$

TABLE IV
RESULTS OF BOUNDARY MATCHING USING SENSITIVITY BASED METHOD

Boundary Nodes	Power Flow Matching	Voltage Magnitude (p.u.)	Voltage Phase Angle (°)	Active Power (p.u.)	Reactive Power (p.u.)
500 kV bus in substation A	Before	0.98694	21.88105	9.79558	1.16632
	After	0.98732	21.87153	9.79617	1.17048
	Error	0.00038	0.00952	0.00059	0.00416
220 kV bus in substation B	Before	0.97084	16.60065	9.31804	2.79947
	After	0.97081	16.59784	9.31624	2.80175
	Error	0.00003	0.0027	0.00180	0.00228
220 kV bus in substation C	Before	0.96570	13.7593	−1.21999	−0.57253
	After	0.96558	13.75452	−1.22100	−0.57750
	Error	0.00012	0.00478	0.00101	0.00497

TABLE V
RESULTS OF BOUNDARY MATCHING USING THE MERGING MODEL

Boundary Nodes	Power Flow Matching	Voltage Magnitude (p.u.)	Voltage Phase Angle (°)	Active Power (p.u.)	Reactive Power (p.u.)
500 kV bus in substation A	Before	0.98694	21.88105	9.79558	1.16632
	After	0.98694	21.87222	9.79378	1.16534
	Error	0.00000	0.00883	0.00180	0.00098
220 kV bus in substation B	Before	0.97084	16.60065	9.31804	2.79947
	After	0.97086	16.59658	9.32078	2.79975
	Error	0.00002	0.00407	0.00274	0.00028
220 kV bus in substation C	Before	0.96570	13.75930	−1.21999	−0.57253
	After	0.96572	13.75519	−1.22055	−0.57243
	Error	0.00002	0.00411	0.00056	0.00010

TABLE VI
BRANCH FLOW IN THE REST OF THE INTERNAL NETWORK USING THE MERGING MODEL

Branch No.	Power Flow Matching	Active Power (p.u.)	Reactive Power (p.u.)
1	Before	−0.52286	−0.27810
	After	−0.52331	−0.27810
	Error	0.00045	0.00000
2	Before	0.20960	−0.39200
	After	0.20954	−0.39201
	Error	0.00006	0.00001
3	Before	2.62398	−0.51225
	After	2.62349	−0.51225
	Error	0.00049	0.00000
4	Before	−0.73422	−0.27282
	After	−0.73424	−0.27280
	Error	0.00002	0.00002
5	Before	−0.45164	−0.15890
	After	−0.45164	−0.15890
	Error	0.00000	0.00000

B. Steady State Simulations

According to the initial states shown in Table I, the boundary power flow in the internal network is supposed to be exact so that the boundary mismatches can be obtained. Using boundary bus tearing, the external network is connected with the internal network via the merging model. The parameters of the merging model can be calculated according to (5)–(7), and listed in Table III. The results of boundary matching using the two methods are shown in Table IV and Table V. It can be found that the matching results obtained using the merging model are more accurate than the results obtained using the sensitivity-based method.

In addition to the errors of the boundary nodes shown in Table V, the errors in the rest of the internal network are also evaluated for the merging model based boundary matching. The states and errors of 5 lines and 5 buses, which are randomly selected in the internal network, are listed in Table VI and Table VII. It can be found that the power flow of the internal network remains unchanged after the network merging.

In theory, the boundary mismatches can be eliminated by the “plug and play” merging model. However, the error is observed in practical application because of the limited accuracy of digits during the filling of data cards in PSD-BPA software, which is used to conduct the calculation. For instance, the phase angle of the phase shifter can only be accurate by up to two decimal places.

TABLE VII
BUS VOLTAGE IN THE REST OF THE INTERNAL NETWORK USING THE MERGING MODEL

Bus No.	Power Flow Matching	Voltage Magnitude (p.u.)	Voltage Phase Angle (°)
1	Before	−0.52286	−0.27810
	After	−0.52331	−0.27810
	Error	0.00045	0.00000
2	Before	0.20960	−0.39200
	After	0.20954	−0.39201
	Error	0.00006	0.00001
3	Before	2.62398	−0.51225
	After	2.62349	−0.51225
	Error	0.00049	0.00000
4	Before	−0.73422	−0.27282
	After	−0.73424	−0.27280
	Error	0.00002	0.00002
5	Before	−0.45164	−0.15890
	After	−0.45164	−0.15890
	Error	0.00000	0.00000

C. Dynamic Simulations

To investigate the transient accuracy of the integrated model obtained by the merging model, both the small signal stability analysis and the dynamic simulations under system disturbance are performed. The Eigen analysis results are shown in Table VIII and IX, and only the inter-area oscillation modes between the internal network and the external network are listed. Theoretically, the power flow of the external grid in the merging model based integrated model and the sensitivity based integrated model are different, so the Eigen analysis results of those two integrated models are also different. However, it can be found in Table VIII and IX that the Eigen analysis results of the two integrated model are similar, because 1) the generators in the two integrated models have the same parameters (e.g., inertia constant of the generators, etc.), 2) the network topologies are same in the two integrated models except for the merging model, and 3) no dynamic elements are included in the merging model, which has little impact on the dynamic response.

TABLE VIII
OSCILLATION MODES OF THE MERGING MODEL BASED INTEGRATED MODEL

No.	Frequency (Hz)	Damping Ratio (%)
1	0.597	10.3
2	0.624	25.7
3	0.653	12.0
4	0.768	13.8

TABLE IX
OSCILLATION MODES OF THE SENSITIVITY BASED INTEGRATED MODEL

No.	Frequency (Hz)	Damping Ratio (%)
1	0.596	10.2
2	0.626	25.7
3	0.663	11.2
4	0.775	12.3

A three-phase grounded fault with a ground impedance of 0.02 + j0.02 p.u. is applied to one of the transmission lines in the external network. The fault occurs at time $t = 1$ s and is cleared after 0.2 s. The dynamics of the bus voltage, the rotor angle differences between the generators, the active power, and the reactive power of the transmission line located in the internal network are shown in Fig. 5. It shows that the dynamics of the integrated model constructed by the merging model fit those constructed by the sensitivity-based method

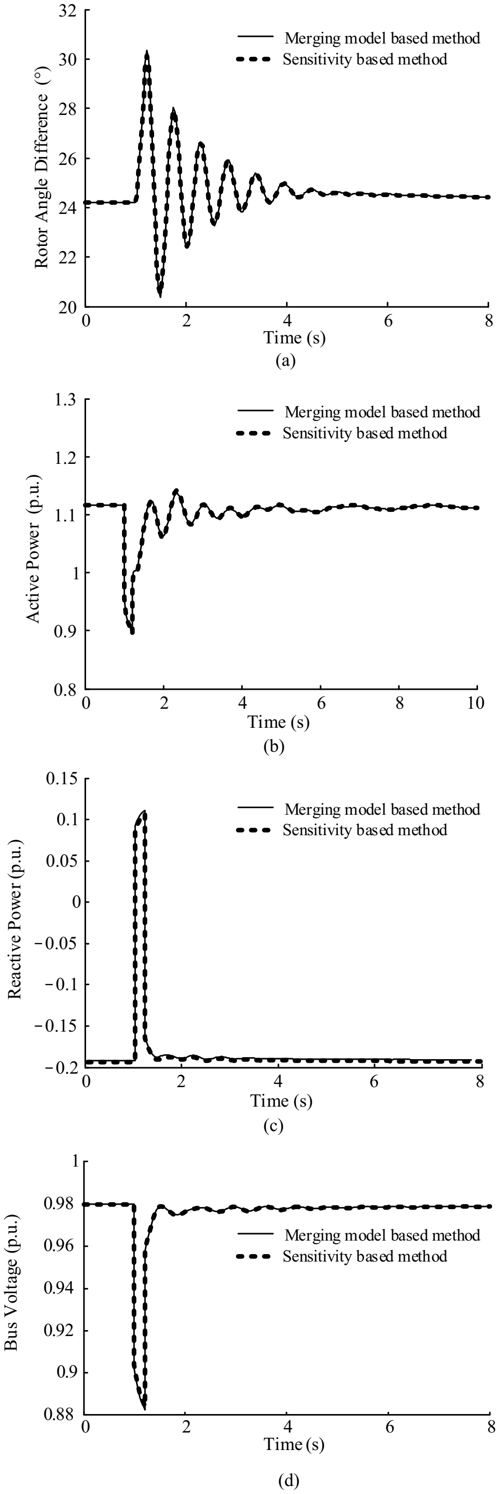

Fig. 5. Dynamics of the internal network after networks merging. (a) Rotor angle difference between the generators. (b) Active power of the transmission line. (c) Reactive power of the transmission line. (d) Bus Voltage.

very well. Thus, the merging model has inappreciable impact on the dynamic behaviors of the integrated model, and the accuracy of the integrated model is satisfying under transient state.

VII. CONCLUSION

In this paper, the distributed online dynamic modeling method for power system is proposed. In this method, a novel multi-area networks merging model, consisting of the phase shifter, transformer, and admittance is introduced to merge the models of the sub-grids with each other and subsequently build the model of the whole system online. Both steady state and dynamic simulations are performed in a real power system. The steady state simulation results indicate that the proposed model can rapidly match the boundary power flow with minimal computations, and the efficiency of the network merging can be improved significantly. Moreover, the power flow of the internal network, which is assumed as the exact value, remains unchanged after the networks merging. Therefore, the steady state accuracy of the integrated model is satisfying. The Eigen analysis and dynamic simulation results indicate that despite the fact the network topology changed after using the proposed merging model, the transient state accuracy of the integrated model was also satisfactory.

REFERENCES

[1] L. L. Li, X. R. Xie, J. F. Yan, and Y. D. Han, "Fast online identification of the dominant parameters of composite load model using Volterra model and pattern classification," in *Proceedings of IEEE PES General Meeting*, 2007, pp. 1–8.

[2] F. Li, W. Qiao, H. B. Sun , H. Wan, J. H. Wang, Y. Xia, Z. Xu, and P. Zhang, "Smart transmission grid: vision and framework," *IEEE Transactions on Smart Grid*, vol. 1, no. 2, pp. 168–177, Aug. 2010.

[3] A. L. Tognete, L. Nepomuceno, and A. dos Santos, "Framework for analysis and representation of external systems for online reactive-optimisation studies," *IEE Proceedings – Generation. Transmission and Distribution*, vol. 152, no. 6, pp. 755–762, Nov. 2005.

[4] P. Hirsch (2005, March). Transmission fast simulation and modeling (T-FSM)—Functional requirement document, US EPRI, USA. [Online]. Available: http://www.intelligrid.info/doc/TFSMFunctionalRequirements-ER11666.pdf

[5] M. Parashar, J. S. Thorp, and C. E. Seyler, "Continuum modeling of electromechanical dynamics in large-scale power systems," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 51, no. 9, pp. 1848–1858, Sept. 2004.

[6] B.K. Choi, H.D. Chiang, Y.H. Li, and H. Li, "Measurement-based dynamic load models: derivation comparison and validation," *IEEE Transactions on Power Systems*, vol. 21, no. 3, pp. 1276–83, Aug. 2006.

[7] R. M. He, J. Ma, and D. J. Hill, "Composite load modeling via measurement approach," *IEEE Transactions on Power Systems*, vol. 21, no. 2. pp. 663–672, May 2006.

[8] K. Nithiyananthan, "A distributed model for multi-area power systems on-line dynamic security analysis," in *Proceedings of TENCON'02* , 2002, vol. 3, pp. 1765–1767.

[9] L. Guo, "Studies on system-wide parameter identification of multi-generators in wide area power system," Ph.D. dissertation, Hohai Univ., Nanjing, China, 2012 (in Chinese).

[10] R. Chen, W. C. Wu, H. B. Sun, and B. M. Zhang, "A two-level online parameter identification approach," in *Proceedings of IEEE PES General Meeting*, 2013, pp. 1–6.

[11] A. P. Meliopoulos, G. J. Cokkinides, F. Galvan, and B. Fardanesh, "Distributed state estimator—Advances and demonstration," in *Proceedings of 41st Hawaii International Conference on System Sciences*, 2008, pp. 7–10.

[12] T. Yang, H.B. Sun, and A. Bose, "Transition to a two-level linear state estimator—Part I: Architecture," *IEEE Transactions on Power Systems*, vol. 26, no. 1,pp. 46–53, May 2011.

[13] T. Yang, H. B. Sun, and A. Bose, "Transition to a two-level linear state estimator—Part II: Algorithm," *IEEE Transactions on Power Systems*, vol. 26,no. 1, pp. 54–62, May 2011.

[14] A. Monticelli, and F. F. Wu, "A method that combines internal state estimation and external network modeling," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-104, no. 1 ,pp. 91–103, Jan. 1985.

[15] A. F. Rahimi, K. Kato, S. H. Ansari, V. Brandwajn, G. Cauley, and D. J. Sobajic, "On external network model development," *IEEE Transactions on Power Systems*, vol. 11, no. 2, pp. 905–910, May 1996.

[16] K. Kato, "External network modeling – recent practical experiences," *IEEE Transactions on Power Systems*, vol. 9, no. 1, pp. 216–228, Feb.1994.

[17] A. Monticelli, "Electric power system state estimation." *Proceedings of IEEE*, vol. 88, no. 2, pp. 262–282, Feb. 2000.

[18] H.B. Sun and B.M. Zhang, "A systematic analytical method for quasi-steady-state sensitivity," *Electric Power System Research*, vol. 63, no. 2, pp. 141–147, Jun. 2002.

[19] W. Y. Jiang, W. C. Wu, B. M. Zhang, G. Wang, and H. B. Sun, "Network model reconstruction in online security early warning system," *Automation of Electric Power Systems*, vol. 31, no. 21, pp. 5–9, Nov. 2007 (in Chinese).

[20] P. Ju, C. Qin, F. Wu, H. L. Xie, and Y. Ning, "Load modeling for wide area power system," *International Journal of Electrical Power and Energy Systems*, vol. 33, no. 4, pp. 909–917, Feb. 2011.

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