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Emergency Coordination and Decision Making over Interconnected Power Systems

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***Abstract*—An interconnected transmission network of power system is composed of several subsystems which are jurisdictionally operated by different System Operators and exhibit global changes instantaneously as a result of local decisions of any operator related to its own grid. The complexity of the coordination and decision making of power systems, an infrastructure which can be represented as a socio-technical system, demands investigations of applicable approaches to simulate and analyze the impacts of different coordination rules on the decision making and the performance of the system, especially under emergency. In this paper, a general framework for modeling the power transmission grids as a complex socio-technical system is proposed. Under the framework, multi-agent systems are employed to simulate the decision making of each system operator and the performance of the whole interconnected system due to their interaction. Different scenarios are designed to compare and analyze the impacts of coordination rules, mainly focusing on the policy for tie-line management and on the information revealed, on the outcomes of the decision making process and on the system performance in terms of transmission network feasibility (i.e. line flow, voltage profile, generator output) with reference to the subsystem and the whole interconnected network. The approach is applied to the IEEE-30 bus system to illustrate its application and effectiveness.**

Keywords—coordination, emergency control, decision making, socio-technical system, multi-agent systems, interconnected power systems, infrastructure

NOTATIONS

$\mathcal{G}$: Set of generators.

$\mathcal{D}$: Set of loads.

N: Total bus number.

$\Delta d_i^p / \Delta d_i^q$: Active and reactive power of load shed at bus i (MW, MVar).

$\Delta P_i / \Delta Q_i$: Active and reactive generation adjustment at bus i (MW, MVar).

V_i / δ_i : Voltage magnitude and angle at bus i.

Y_{ij} / θ_{ij} : Amplitude and phase angle elements of admittance matrix located at i-th row and j-th column.

P_i^0 / Q_i^0 : Active and reactive power generation before adjustment at bus i (MW, MVar).

d_i^{p0} / d_i^{q0} : Active and reactive load power consumption before shed at bus i (MW, Mvar).

P_i^m / P_i^M : Min/max active power generation at bus i (MW).

Q_i^m / Q_i^M : Min/max reactive power generation at bus i (Mvar).

d_i^{pm} / d_i^{pM} : Min/max active load power at bus i in terms of value (MW).

d_i^{qm} / d_i^{qM} : Min/max reactive power consumption at bus i (Mvar).

$\delta_{ji}^m / \delta_{ji}^M$: Min/max difference of angles at bus i and bus j (degree).

F_{ij} : Power flow on transmission line i-j (MVA).

F_{ij}^m / F_{ij}^M : Min/max power flow on line i-j (MVA).

V_i^m / V_i^M : Min/max voltage value at bus i (p.u.).

I. INTRODUCTION *(HEADING 1)*

Power systems are of critical importance in the functioning of modern society. The ongoing liberalization of traditional vertical integrated power industry and the interconnection of different power systems over a continent wide area raise a series of physical and social problems to the operators and regulators of power systems.

The power systems share the same important features with other socio-technical systems [1], [2]. From the *technical* point of view they are huge infrastructures that all the power flows over the transmission system must obey the power flow equations while the system to be kept feasible needs to satisfy a set of physical and operational constraints related both to the components (generators, loads,..) and to the transmission system (line flows,…). This framework distinguishes power system from other infrastructures and makes its operation more challenging.

From the *social* point of view, the society has expectations to the performance of the system in terms of its feasibility, supplying power without interruptions and major blackouts and low cost of supplying electricity. Humans have knowledge and resources to collectively develop appropriate approaches to operate the system, but the level of the performance is strictly related to the corresponding investments and some trade-off analysis needs to be implemented.

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In addition, the interconnected power grids, managed by several system operators (SOs), exhibit network-wide changes instantaneously as a result of local decisions of any SO on its own grid. Therefore a set of effective coordination rules are required to achieve a better global performance of the interconnected system as well as an acceptable performance of each subsystems; the balance of global and local performance is a key issue in the coordination of power transmission grids.

Many studies have been performed on SO's decision making to operate and control the power system under emergency. Reference [3] converts the emergency problem into a feasibility checking problem and solves it based on the Ordered Binary Decision Diagram (OBDD) searching method. Reference [4] uses security-constrained unit commitment model to obtain the minimum bid-based system operating cost for steady state contingencies. Reference [5] takes a measure of the economic equivalent of security and reliability as object function to optimize the coordination of preventive and emergency control using Benders decomposition. Few investigations have taken into consideration of the coordination of the decision making of various SOs' under emergency circumstances.

The problem is complex in its nature due to the interaction of multiple aspects such as the global and local performance, the social and technical issues, the regulatory/decision making and physical levels, and the ambiguity in the coordination of multiple decision makers both from the theoretical and the computational point of view. Multi-agent system (MAS) is one of the possible theoretical frameworks for addressing the problem and it has been successfully used in many aspects related to power system analysis and simulation. Reference [6] uses MAS to simulate the emergency control of a single SO. Reference [7] adopts the multi-agent system to search for the system equilibrium under malicious attacks and tries to study the vulnerability of power system with reference to the dependency on information exchange. Reference [8] presents a multi-agent approach to power system restoration.

In this paper, we propose a general framework for the emergency coordination and decision making over interconnected power systems by using MAS approach. The model proposed is somehow "conceptual" and does not consider yet more detailed representation of power system operation such as power-frequency regulation, reconfiguration of topology of the network, adjustment of the transformers' taps, which could be of course added in the model. The rest of the paper is organized as follow. Section II describes the power system as a socio-technical system; issues about power system operation and coordination under emergency are discussed in section III. The model of coordination of different SOs based on MAS is presented in section IV while section V illustrates the proposed methods on the IEEE-30 bus system. Some conclusions are drawn in Section VI.

II. POWER SYSTEM AS A SOCIO-TECHNICAL SYSTEM

The term "socio-technical system", refers to the interaction between society's complex infrastructures and human behavior, and was coined firstly by Eric Trist and Fred Emery in the 60s. As a complex fundamental infrastructure, the operation of power system shows a considerable interplay among physical, technological, economic, institutional and human factors.

The performance of the physical system definitively depends on the physical laws; for example, the power flows over the network and power injection and withdrawal are governed by power flow equations based on the "Kirchhoff laws" and can not be overcome. In addition, the power grids need to be operated under strict physical and operational constraints such as the generation limits, the line flow limits, the static and dynamic stability limits, etc. On the other hand, reliability, security, efficiency and economy, as an expression of the willingness of human, are expected and required when operating the systems. The complex interactions among the human, the physical and the cyber layer (that acts as an interface between the human and the physical layers and vice versa) together determine the performance of the power system with very specific feature of this environment.

Moreover, the interconnection of various subsystems into a unique grid, like UCTE over the European continent which is composed of 5862 buses, 7970 branches, 34 SOs and 23 member countries, outlines the complexity of the socio-technical system. Each system operator has jurisdiction over a specific part of the interconnected system and pursues individual objectives, usually represented by the local performance of the sub-system while complying with some coordination rules to contribute to the overall performance of the interconnected system. On the institutional level, the cooperation of various SOs is quite loose and rather ambiguous due to the lack of uniquely defined and detailed overall objectives, effective incentives and strong administrative control actions and sanctions.

To take all the layers and their interplay collectively into consideration, we proposed the general framework to map the complex socio-technical systems as shown in Fig.1. The subsystems operated by various SOs connect with one another physically to integrate into a unique grid. A SO operates his/her corresponding subsystem respectively to maximize his/her individual objectives, subjected to the physical and operational constraints as "inside" constraints and coordination rules as "outside" obligations. Measurements from the physical layer are sent to the relevant SO as the input of the decision making process, while the commands, such as network reconfiguration, load shedding, generation adjustment, etc. transferred to the physical layer are the output of the decision making. Information from the other SOs might be very valuable to assist the decision making, hence under the coordination rules subset of the information concerning the operational data can be exchanged among SOs.

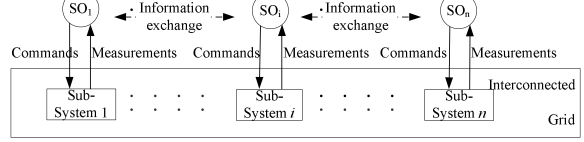

Figure 1. Framework of coordination

Due to the interconnected structure of the whole system, any failure within a subsystem will affect simultaneously the whole grid and eventually may evolve to a cascading failure to the whole system. The US-Canada outage and the Italian blackout in 2003 affected more than 50 million people and 57 million people respectively provide very good examples of how a lack of coordination under emergency can result in serious failures of one or more subsystems.

III. POWER SYSTEM OPERATION AND COORDINATION UNDER EMERGENCY

According to Dy Liacco and Fink and Carlsen [10], a power system can be operated in 5 different states: *normal*, *alert*, *emergency*, *extremes* and *restoration*.

Power system is typically operated in normal state for more than 99% of the time, but it is easy to suffer disturbance during operation. Severe disturbance can possibly transfer the power system into emergency state in which some components are overloaded and some physical or operational constraints are violated; in this situation the system may start to disintegrate. It is the most urgent that the SO launches emergency control actions to restore the normal operating conditions. The transition to/from different states is depicted in Fig2.

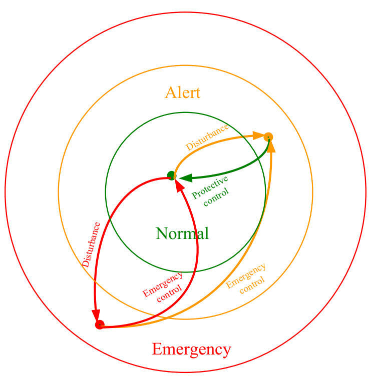

Figure 2. Transition to/from different operational states

In real cases, the state boundary is not always uniformly defined. Each system operator or national regulator decides some criteria or standards to guide the preventive and emergency control actions, following some national/international standards. For example, North American Electric Reliability Corporation (NERC) [11] approves a set of reliability standards which are categorized by different emergency situations and are requested to be complied with by its members; SOs, such as PJM [12], work out their own guides for emergency control in addition to the compliance with NERC standards. Reference [16] describes the emergency procedures of UCTE, including system operation in insecure conditions and system restoration after collapse. Many literatures [13][15] adopt some indications or indices to point out the boundary, static or dynamical, of every state implicitly or explicitly.

Besides distinguishing the operational states which determine the context of different decision making procedures for a SO, the coordination rules that are superior to the local institutions are also vital to the interconnected SOs. Such coordination rules contain the mandates for information exchange, cross-border actions, tie-lines management, etc. For example, UCTE asks to its member to take immediately all possible measures to restore normal operating conditions under emergency conditions, subjected to the means and resources available at that time. Furthermore, all SOs have to notify the neighboring SOs and ask for cooperation [16].

Different coordination rules may result in different decision making output in terms of commands from the SOs and finally lead to different performances, blackout or restoration, of both the interconnected system and subsystems.

IV. COORDINATION OF SOS AS MULTI-AGENT SYSTEM

Multi-Agent Systems (MAS) may be regarded as a context in which a population of autonomous agents, which interact with each other through and within an environment, pursuing individual objectives and being able to communicate and interact among themselves and with the environment; the superposition of the individual behaviors of the agent determines the status of the system as a whole and its performance. The agent can adapt itself based on the changes occurring in its environment, so that a change in circumstances will still strive for the intended result. The autonomy, social ability and adaptation of an agent provide the way to simulate the complex systems which is collectively determined by the interactions of multiple actors and layers.

The challenge posed by modeling the complexity of coordination and decision makings of multi-players and multi-levels is that no general analytical model can be adapted to represent the performance of the overall system. It can be only modeled as the result of the integrations of a multitude of self-interested agents interacting with an environment and among themselves through an environment.

Based on the discussion in the previous sections, multi-agent systems are employed to describe the coordination and decision making of SOs over the interconnected system. From each agent's point of view, the behaviour in terms of interactions with the environment can be represented as in Fig3.

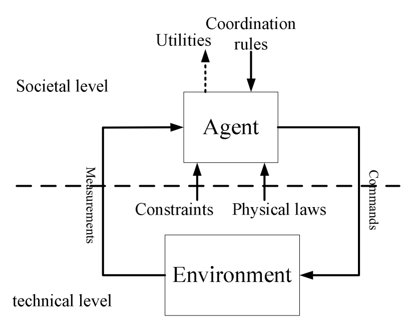

Figure 3. MAS for coordination and decision making

Each SO, under emergency, aims at minimizing the energy un-served to the loads, given the coordination rules he needs to comply with; if that is not technically feasible it will curtail loads starting from the less sensitive ones. Let's divide the loads into two sets *interruptible* ($\mathcal{D}_I$) and *superior* ($\mathcal{D}_S$). The interruptible loads are the ones that, also due to special economic incentives or rates, can be curtailed by the SO under emergency control, while the superior loads are the ones that should be supplied and can only be interrupted of last resort only under severe emergency.

The decision making problem of the SO in this context can be formulated as:

$$\min_{\substack{\Delta P_g, \Delta d_i^p \\ \Delta Q_g, \Delta V_i \\ \Delta \delta_i}} \sum_{i \in \mathcal{D}_S} \Delta d_i^p = \sum_{g \in \mathcal{G}} \Delta P_g - \sum_{j \in \mathcal{D}_I} \Delta d_j^p \quad (1)$$

s.t.

$$\sum_{j=1}^{N} V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) - (P_i^0 + \Delta P_i) + (d_i^{p0} - \Delta d_i^p) = 0 \quad i = 1, \cdots, N \quad (2)$$

$$\sum_{j=1}^{N} V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) - (Q_i^0 + \Delta Q_i) + (d_i^{q0} - \Delta d_i^q(\Delta d_i^p)) = 0 \quad i = 1, \cdots, N \quad (3)$$

$$P_i^m \le P_i^0 + \Delta P_i \le P_i^M \quad i \in \mathcal{G} \quad (4)$$

$$Q_i^m \le Q_i^0 + \Delta Q_i \le Q_i^M \quad i \in \mathcal{G} \quad (5)$$

$$d_i^{pm} \le d_i^{p0} + \Delta d_i^p \le d_i^{pM} \quad i \in \mathcal{D} \quad (6)$$

$$d_i^{qm} \le d_i^{q0} + \Delta d_i^q(\Delta d_i^p) \le d_i^{qM} \quad i \in \mathcal{D} \quad (7)$$

$$V_i^m \le V_i \le V_i^M \quad i = 1, \cdots, N \quad (8)$$

$$\delta_{ji}^m \le \delta_{ji} \le \delta_{ji}^M \quad j, i = 1, \cdots, N \quad (9)$$

$$F_{ij}^m \le F_{ij} \le F_{ij}^M \quad j, i = 1, \cdots, N \quad (10)$$

$$\frac{\Delta d_i^p}{d_i^{p0}} = \frac{\Delta d_i^q}{d_i^{q0}} \quad i = 1, \cdots, N \quad (11)$$

(2) and (3) represent the power flow equations (real and reactive power balance at each bus); (4)–(5) and (6)-(7) are real and reactive power limits of each bus for generators and loads; (8) and (9) are the stability limits taking into account of the voltage profile and phase angles; (10) incorporates the line flow limits while (11) fixes the power factor at each load bus affected by curtailment.

The simulation of the operation of the interconnected power systems is based on a continuous sensing of the status of each subsystem by the related SO; if the subsystem has moved to an emergency state, the system operator would be compelled to undertake proper control actions. The objective of the decision making is to minimize the load curtailment after the restorative actions have been undertaken. The decision variables under the control of the SO are, with reference to its own system, the generation redispatch, the curtailment of interruptible loads or the shedding of superior loads; the three actions are undertaken in the order in which they are listed till normal state is restored. The decision making process is modeled by the optimization problem (1)-(11). The decision making is performed, as a result of the rising of an emergency, by all the SOs at the same time; consequently, the status of each subsystem and the power system as a whole will change and again the SOs may be called to make decision and perform actions on each subsystem. This process, represented by a sequence of iteration, will go on till a Nash equilibrium, if existing, is reached or the system will face a global blackout.

Though avoiding a global blackout is, obviously, a critical objective of the interconnected systems, any failure of any subsystem can spread over the whole network and result in multiple actions taken by various SOs. However, if the fault is severe enough, corrections can not be made to restore the network; after several iterations, no SO can get any command from decision making process, a special equilibrium will be reached -- global blackout. The institutions of coordination and actions taken by different SOs will impact the equilibrium and the number of equilibria. In this paper, we assume the existence of equilibrium and then verify it ex-post.

The whole procedure can be illustrated as in Fig 4.

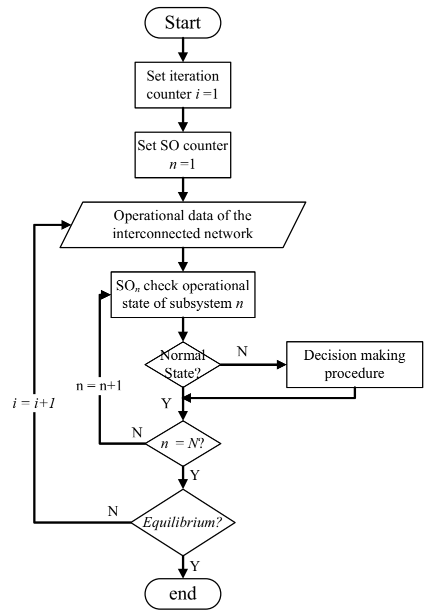

Figure 4. Flow chart of simulation process

V. NUMERICAL STUDIES

In this section, taking IEEE-30 bus test system as a study case (Appendix A1) in which 3 SOs are assumed, we show how the proposed model can be applied; particularly we use the model to assess the influence of two aspects of the coordination rules, i.e., *information set* and *tie-line management policy*, on the decision making outputs of each SO and on the system performance. The first refers to the dimension of the information set, in terms basically of the number of buses of the neighboring subsystems that each SO possesses when building the network model for its decision making. The second is related to the constraints on power flow control on the tie-lines under emergency.

We consider two different coordination scenarios and simulate the coordinated outcomes of various SOs under two different contingencies.

The coordination scenarios are:

S1- Keeping fixed, by each SO, the power flow on the tie-lines with neighboring systems and dimension of the information set equal to k (the first k buses closest to the border of each neighbor)

S2- Cutting off the power exchange with neighboring systems.

In the scenario *S1,* the tie-line policy imposed by the regulator compels each SO to operate with the goal of maintaining the existing power flow exchange with the other systems even if a curtailment of those flows could alleviate its own problems. In this scenario *k* is the size of the information set of each system and different values of *k* can represent different rules about the information revealed by each SO to the others and the level of detail in the network representation adopted by the SO when making decisions.

In the scenario *S2* each SO, under emergency, firstly sacrifices the power exchanges with other areas by curtailing the power flow of the tie-lines and, naturally, in this case no information about other SOs is needed.

The contingencies, considered as a trigger for the coordinate decision making process, are:

C1. Outage of line 21-22 and line 6-8

C2. Outage of 2 generators: located at bus 2 and at bus 23, respectively in 2 different subsystems.

Contingency *C1* refers to a case in which simultaneously two heavily loaded transmission lines in two different systems have failures; while contingency *C2* refers to the case in which two generators in two different subsystems are triggered out simultaneously due to failures and result in the defect of power supply.

The results of the simulation are summarized, for both scenarios, in Table1 and Fig.5 and Fig.6 for contingency *C1* and in Table2 and Fig.7 and Fig.8 for contingency *C2*.

TABLE I. SIMULATION RESULTS FOR CONTINGENCY *C1*

		After Contingency	After Restoration			
			Iteration	*Load curtailment (%)*	*Generation adjustment %*	
					$\sum G^{+}$	$\sum G^{-}$
S1	k = 1	$V_8 < V_8^{\min}$ $F_{8-28} > F_{8-28}^{\max}$	1	-2.002	2.763	-4.196
			2	-0.006	0.065	-0.072
			Total	-2.008	2.828	-4.268
	k = 2		1	-2.004	4.968	-6.415
			2	-0.005	3.492	-3.478
			Total	-2.009	8.460	-9.893
S2			1	-3.193	30.367	-32.747
			Total	-3.193	30.367	-32.747

From Table 1 we can see that for emergency state due to the contingency *C1*, the impacts of tie-line policy are more profound than the size of the information set.

The percentage of load curtailment in scenario *S2* is larger than that in *S1*, and also the same for the adjustment of generation. In *S2* the adjustment percentage of generation is comparatively 4-11 times greater than in *S1* because the actions of curtailing the tie-line power immediately under the emergency will induce the lack of backup between neighboring areas. Each SO needs to redispach its own subsystem independently, which increases the adjustment of each subsystem and eventually increases the total adjustment of the interconnected system.

The percentages of load curtailment in *S1* for both $k = 1$ and $k = 2$ are almost the same; on the other hand, the information affects the decisions of SOs in terms of generators' set-points. For both $k = 1$ and $k = 2$, the sums of the increase and decrease of the generation are almost the same, but they are quite differently allocated among the units' increase and decrease.

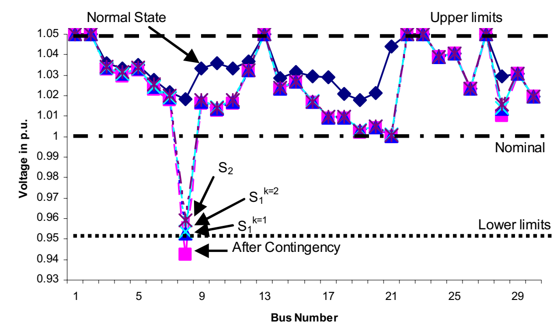

Figure 5. Voltage profiles for emergency *C1*

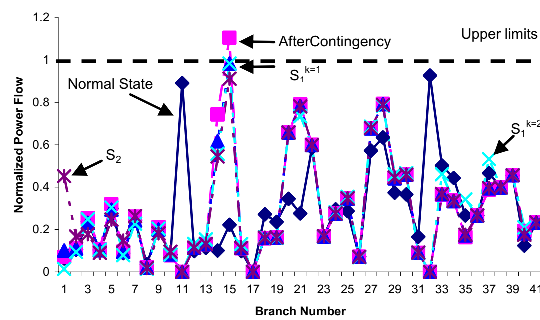

Figure 6. Normalized power flows for emergency *C2*

The performance of the system after the contingency is assessed in terms of the voltage profile and the flows on the system lines with reference to the rated values (Fig.5 and Fig.6).

After contingency *C1*, both voltage and line flows constraints are violated. The decision making of the SOs, within the first 2 iterations, can, in this case, bring the system back from the emergency state to a normal state that corresponds to equilibrium. Table 2 lists the simulation results of the 2 scenarios under emergency *C2*.

TABLE II. SIMULATION RESULTS FOR EMERGENCY *C2*

	After Contingency	After Restoration		
		Iteration	*Load curtailment*	*Generation adjustment %*

				(%)	$\sum G^{+}$	$\sum G^{-}$ *
S1	k=1	$P_{g1} > P_{g1}^{\max}$	1	-11.74	31.77	-43.06
			Total	-11.74	31.77	-43.06
	k=2		1	-23.71	19.53	-43.06
			Total	-23.71	19.53	-43.06
S2			1	-9.627	33.77	-43.06
			Total	-9.627	33.77	-43.06

Note: * the generation decrease includes the active power loss from the triggered out units

In the case of contingency *C2* (Table 2) the impacts of the size of the information set are more important than those related to the policy for tie-line management; the decremental adjustment, which equals the lost power of generators at bus 2 and 23, is identical for all the scenarios. In scenario *S2* the load curtailment is the minimum due to the independent and local redispatch of generators in such a way that each SO can decrease the cross-border power transmission which slightly decrease the total system loss. Thus fewer loads should be curtailed if compared with *S1* with $k = 1$.

In *S1* with $k = 2$, the demand of operational feasibility for more buses out of his/her control drastically increases the difficulties for the SO who needs to make decisions to minimize his/her load curtailment while complying with the coordination rules. When SO makes decisions, more buses of neighboring subsystems informed implies more consideration of buses beyond his/her control. The fact that the SO is not entitled the jurisdiction to control those buses prohibits his/her use of the resources at those buses to correct the subsystem with the subset of the neighboring subsystems informed together back to normal state. Mathematically, it adds more constraints to the optimization problem and may result in the diminishment of the feasible region or even becoming infeasible. In this case, more loads should be curtailed to obtain feasibility of the system.

Fig.7 and Fig.8 show the details of generation adjustments and load curtailment after emergency *C2* in all scenarios. After the failure of generators at bus 2 and 23, generator at bus 1 skyrockets from 26% to 128% of its capacity because the generator at bus 1 is selected as a slack generator who needs to balance the loss of the whole system and other defects between generations and loads. Except for generator at bus 1, the rest of generators produce almost the same power in all scenarios. It is also worth noting that the adjustment curves (Fig.7) in *S2* and *S1* with $k = 1$ almost overlap, implying the total load curtailment should be the same as well if the tiny difference in system loss is neglected (Table 2).

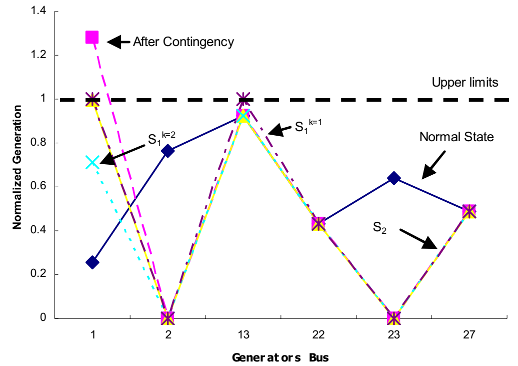

Figure 7. Generation adjustment for emergency *C1*

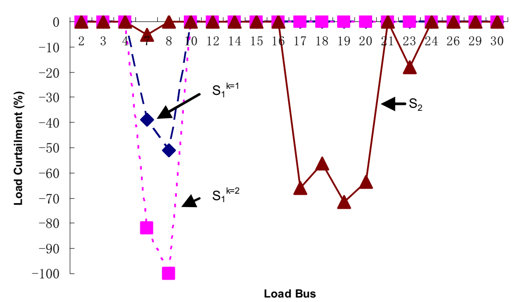

Figure 8. Load shedding for emergency *C2*

Although the sum of the load curtailed in *S2* and *S1* with $k = 1$ are identical, their allocation among loads are quite unlike. In *S2*, the loads need to be curtailed distributed among 6 buses, 5 of which locate within subsystem 2 (Fig.8 and Fig.9). In *S1* with $k = 1$, the loads that have been curtailed are at bus 7 and 8 within subsystem 1, while SO2 does not need to interrupt any load since SO1 must export energy to SO2 so that SO1 needs to curtail his/her own load to comply with the coordination rules.

Besides obeying the coordination rules, the impacts of more information as we pointed out before raise the load curtailment under *S1* with $k = 2$.

In addition, in all scenarios, we find the Nash equilibrium at which the systems with reference to the subsystems and interconnected grid are restored back to normal state in the first iteration.

VI. CONCLUSIONS

In the interconnected power systems which exhibit interactions and interdependencies between subsystems, decision makers play to maximize his/her own utilities under the compliance with both technical and social constraints. A challenge is to formulate the social aspects which have not been studied thoroughly and even still formidably defined.

This paper makes a different study about coordination and decision making over interconnected power systems with reference to integrally regarding the huge complex system as a socio-technical infrastructure and proposes the framework to capture the influences from the societal level on the technical level which collectively determine the decisions from each decision makers and the performance of the system. It also provides an approach to study impacts of technical constraints posed to the designs and operations of huge infrastructures.

The coordinated restore of interconnected power transmission grid under emergency can be modeled base on this framework. Under the framework, MAS are appealed to simulate the decision making and interactions. As the simulation has shown, under different emergencies, the information set and the policy for tie-line management can be of different importance.

The framework and approach used in this paper can be easily modified and extended in the future according to various requirements such as different coordination rules concerning frequency regulation and/or different context such as market environment, etc.

APPENDIX

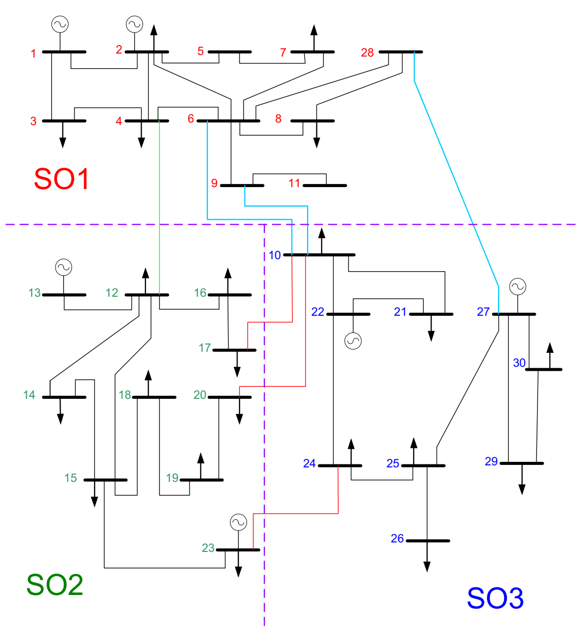

Figure 9. IEEE-30 bus system

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