Optimal Operation of Distribution Grids: A System of Systems Framework

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***Abstract*--There are many entities in the modern power systems that collaborate together to operate the system in a secure and reliable manner. Each of the entities is managed and operated autonomously and intends to increase its own benefit. This paper presents a system of systems (SOS) framework for optimal operation of distribution grids. The distribution grids are modeled as the SOS utilized by distribution companies (DISCOs) collaborating with different loads and microgrids. In this framework, the DISCO and microgrids are regarded as the individual systems which are independently managed and operated aiming at maximizing their own profit. Considering the correlation among the independent systems, the ORIGIN and CLIENT data are introduced and the relationship table is constructed to represent the correlated variables between the entities. The relationship table indicates the sequences of the optimization problems for the entities. The proposed framework is applied to a typical distribution grid and results are discussed.**

***Index Terms*--System of Systems (SOS), optimal operation, distribution grid, distribution Company, microgrid, relationship table.**

I. Introduction

The electricity industry around the globe is undergoing vast progress and evolving into a distributed and competitive industry. As a necessary issue in the power system restructuring, three components of electric power industry, generation, transmission and distribution, are decomposed and each of which are functioned as the separate entity [1]. A generation company (GENCO) operates and maintains the power plants and has the opportunity to sell the electricity to market participants [1]. A transmission company (TRANSCO) utilizes the transmission network to deliver power from producers to consumers [1]. Many other entities are introduced to participate in the competitive electricity markets. All of these entities intend to efficiently contribute to the market and increase their own benefit [2].

As an important entity, a distribution company (DISCO) purchases electricity from the wholesale market or generator companies and distributes this electricity to the final customers in a certain geographical region [3]. In traditional distribution networks, there are no generation sources. Thus, the DISCO only transfers power from the transmission grid, at a high voltage level, toward the consumers. Such a system has high energy loss and produce large amount of heat which is detrimental for the environment. Another undesirable issue of the inactive networks is that these types of networks cannot work in islanded operation mode [4]. Modern distribution grids are active systems consisting of many distributed generations (DGs) [4]. These types of systems support end-users and are connected to the microgrids which are able to produce electricity. In the active distribution grids, the electric power can be transferred in both sides, from low voltage level to high voltage level and vice versa. Utilizing the DGs installed near the load centers causes reducing the system energy loss and heat produced by the system and increasing system reliability and security [5].

Installing the DGs in the distribution networks brings many new challenges into the system. Coordination between DGs and the grid, balancing between generation and consumption, considering the operating cost of the DGs on the locational market price (LMP) and system operating cost, and etc, are among these new challenges [6]. Appropriate strategies for modern distribution networks operation and control are required. While each entity tries to increase its own benefit, the DISCO, all microgrids and consumers collaborate to ensure secure and reliable system operation. The competition and collaboration of different entities can be illustrated based on the system of systems (SOS) concept. A SOS is described as incorporation of task-oriented or dedicated systems in a unique system in which its components: 1) collect their resources and capabilities to construct a more complex system that has more capability and performance than simply the sum of the basic systems, and 2) are able to independently perform valid functions in their own right and continue to work to fulfill those purposes when are separated from the overall system [7].

In this paper, a system of systems framework is presented for optimal operation and planning of distribution grids. In this framework, the DISCOs and microgrids are autonomous entities being managed and operated independently. The framework regards the distribution grid, which is operated by DISCO, as a system of systems interrelated with microgrids and consumer entities. The DISCO, microgrids and consumers are the independent entities that aim at increasing their own profit. Taking into consideration the correlation among the DISCO, microgrids and consumers, ORIGIN and CLIENT data are introduced and the relationship table is constructed to represent the interrelated variables between the entities. This

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relationship table defines the sequences of the optimization problems for the entities. For all systems, the optimization model in this paper is the mixed-integer nonlinear optimization problem, and the sequential quadratic programming technique is used to solve it. The proposed framework is applied to a typical distribution grid and results are discussed.

II. Distribution Grid as a System of Systems

Previously, the distribution networks were inactive systems without the generation source. In these types of systems, the distribution companies (DISCOs), which are usually responsible of secure operation and control of the distribution networks, purchase power from wholesale energy market and sell to consumers. There are a few entities in such a distribution system working together to ensure system security and reliability while each entity aims at increasing its own benefit. The power flow in such a system is unidirectional, from upstream transmission grid toward the distribution grid and end-use customers. On the other hand, the DISCO pays the wholesale energy market to buy power. The DISCO may also pay the customers for load shedding, and the customers pay the DISCO to purchase power. Fig. 1 shows the power flow and cash flow direction in the inactive distribution networks.

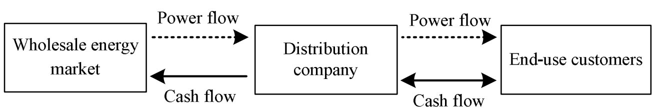

Fig.1. Power flow and cash flow directions in inactive distribution networks.

Recently, different types of DGs have been widely installed in the distribution networks near the load centers to locally support the consumers. The DGs might include wind, hydro, photovoltaic (PV), fuel cells, gas turbines, batteries, ultra-capacitors, and flywheels. The combination of DGs and loads in a certain geographical region might define a microgrid. The microgrid (MG) concept refers to the situation in which different factors, such as geographical, economical and air pollution conditions, make the collect of loads and DGs come together with a management and control scheme supported by a communication foundation that monitors and controls generating units and loads [8].

Compared with traditional distribution networks, the modern distribution networks are active systems which encompass several MGs and end-users. In such an active system, power flow analysis is more complicated than that in inactive systems. While in traditional system, power flowing in the lines is unidirectional and is from high voltage grid toward low voltage system, in modern systems, the power flowing in the lines is bidirectional [4]. And, the power generation sources may contribute in the electricity market intending to sell the electricity and gain the benefit [9]. The power flow and cash flow directions in active distribution networks are depicted in Fig. 2.

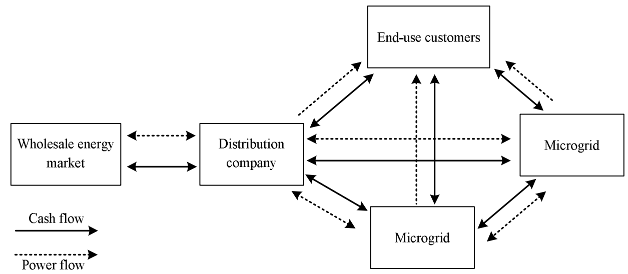

Fig.2. Power flow and cash flow directions in active distribution networks.

Usually, the MGs are independent systems which have their own operation and control regulations. They are connected to the DISCO which is responsible of coordinating these autonomous systems. Thus, the modern DISCO might be defined as a system including different independent systems. When all systems collaborate together to improve security and reliability of the whole distribution system, each independent system intends to increase its own benefit. Hence, the operation and control of the DISCO can be described based on the concept of system of systems engineering (SOSE).

A SOS is identified as a group of components that are separately considered as systems and which are both administratively and operationally self-governing. Operational autonomy means that if the SOS is disassembled into its individual systems, these systems have to be capable to suitably operate independently to perform valid functions in their own right and continue to work to fulfill the customer purposes [7], [10]. Fig. 3 depicts a typical SOS including four independent systems. The systems 1 to 4 have common parts with the SOS and each of which has its own independent design requirements. While the systems 1 and 2 only collaborate with SOS, the systems 3 and 4 collaborate with each other and also SOS. Also, the subsystems 1 and 2 fall within SOS implying they are an integral part of SOS and do not have operational independence.

Although there are many similarities between systems engineering and system of systems engineering, but they are different field of study. The traditional systems engineering intends to find the optimal operation point of and individual system. And SOSE tries to find the optimal operating point of the networks including interacting systems that work together to satisfy various objectives when guarantee constraints of the systems [11].

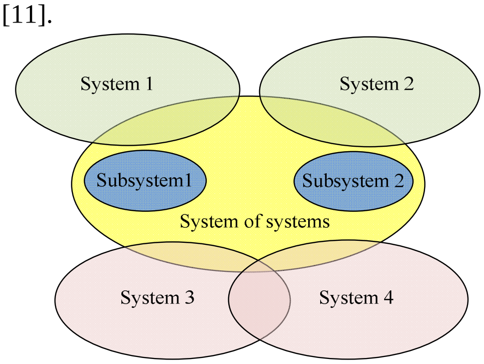

Fig.3. A typical system of systems.

III. SOS Framework to Find Optimal Grid Operating Point

The modern distribution grids are the SOSs including several independent systems such as DISCO, MGs and end-use customers. In the system of systems, the main challenge is to find the most suitable operating point, in that, the SOS achieves its pre-specified tasks, and each independent system reaches its own objectives. Therefore, a compromising is required between the operating point of all autonomous systems and the SOS operating point.

In this section, a system of systems framework is presented to find the optimal operating point of the modern distribution grids. In system of systems engineering, the decision makers needs to understand many concepts and processes, such as the procedure of SOS operation, the interaction between the systems, and the impact of systems to each other. Hence, to provide the appropriate information and understanding for the system operators as the decision makers, the proposed SOS framework includes the following characteristics:

- **Decision variables and constants**: These variables are defined for each system of SOS.
- **Data flow information**: It illustrates the process of the flowing data between individual systems.
- **Variable relationship**: The relationship table depicts that a variable of a system has different types of relationships with another one such as CLIENT and ORIGIN. CLIENT stands for a system that needs information to run its optimization. ORIGIN stands for a system that collaborates and distributes the value of a variable.
- **Data updating procedure**: It shows that how a variable of the ORIGIN system updates variables of the CLIEN system(s).
- **Optimization model**: A multi-step optimization model is required to find the optimal operating point of the SOS.

To clarify this framework, it is illustrated based on a typical distribution grid, shown in Fig. 4 and 5, including a DISCO and three MGs and seven end-use customers. It is assumed that a DISCO is responsible for the distribution grid operation and planning. The DISCO purchases electricity from the wholesale energy market and sell it to the end-use customers based on the retail energy price. Each MG has its own operator which aims at finding the optimal MG operating point. According to different factors, the MG operator may decide to buy/sell energy from/to the DISCO. Hence, a MG might play the role of end-use customer or the power provider.

In the following sections, at first, the data flow information between the systems is explained and the relationship table of the SOS is extracted. Then, in the second section, based on the relationship table and the data requested/required by the systems, the optimal system of system operating point is defined.

A. Data flow and relationship table

Each entity of SOS needs to communicate with other entities, to perform its optimal operation. To better understand the SOS, a visualization of data processing and communication is required. A general idea to visualize data dependencies among systems is data flow, which is a graphical demonstration of the flow of data among systems to model the overall operation. Each arrow shows a flow of data from an origin system (ORIGIN) to the client system (CLIENT). It depicts that such a system needs data from which systems and what kinds of data are input and output.

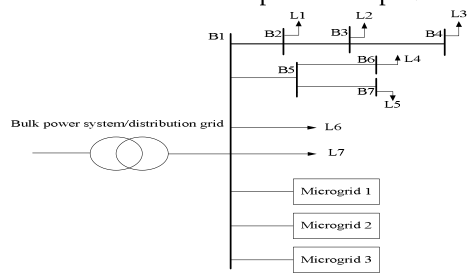

Fig.4. A distribution grid including 3 microgrids and 10 end-use customers.

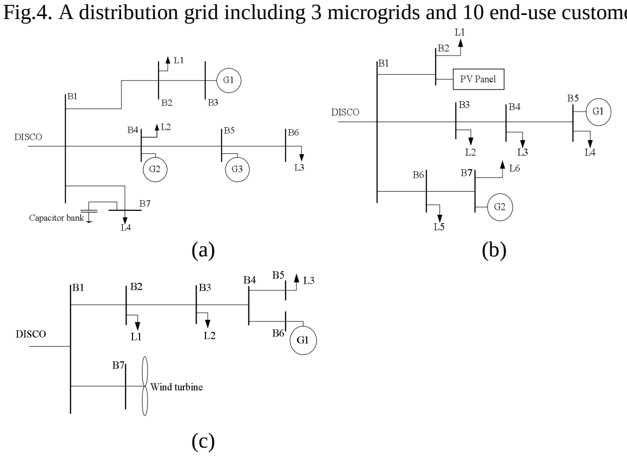

Fig.5. a) MG1, b) MG2 and c) MG3 connected to the distribution network.

Fig.6 shows a data flow between three microgrids and the DISCO of the distribution system of the Fig.4. Two types of data transfer between and microgrids are recognized as follow:

1- DISCO specifies the price of selling and buying of the electricity. The price is an underlying data for microgrids to make decision to employ their own power generation units and energy they need to purchase from or can sell to DISCO. In this case, DISCO is ORIGIN of data and microgrids are CLIENT of data.

2- DISCO needs information about net energy that microgrids need to buy or want to sell. Based on this data, DISCO can run its optimization to buy power from upper level transmission system and manage its load shedding at the minimum price. In this case, Microgrids are ORIGIN of data and DISCO is the CLIENT.

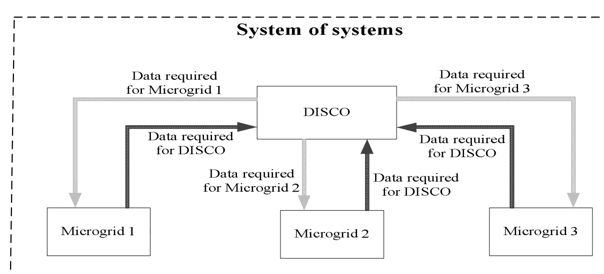

Fig.6. Data flow in the SOS.

Another issue of data communication in a SOS is data updating procedure. Data updating is an inter-system procedure, in that, a system updates other systems about the latest value of a certain variable. For data updating three different modes exist:

1- Upon request mode: When a system requires update value of a variable, it sends its request (REQ) to the system which is the origin of data (ORIGIN). ORIGIN transmits the most update data to the CLINET once received the REQ.

2- Event-driven mode: In event-driven mode data streams when a state in the ORIGIN is amended. ORIGIN triggers a pre-specified event-handling procedure and update CLINETs. Event-driven mode is the fastest mode of updating. Also, it minimizes the network traffic. The main drawback about event-driven mode regards its reliability, as the CLIENT is not able to distinguish whether no update occurs or communication network fails to transfer the new value of data.

3- Periodic mode: The ORIGIN updates CLINETs by latest value of the variable after duration of time. Periodic mode increases the reliability of the communication, however, it increases the network traffic. Moreover, CLINET will not be informed about the variable once data changes, but they have to wait until ORIGIN sends the update.

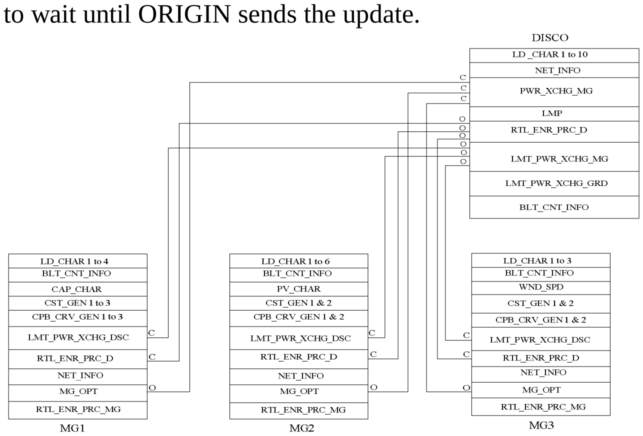

Fig.7. Relationship table for the SOS shown in Fig.4 (C=CLIENT and O=ORIGIN).

In Fig. 6, each arrow from a system to another is group of variables, each of which has its own specifications, such as data type and updating mode. A data flow can be shown in a more detail diagram, named *relation table*. Relationship table subdivided each system to its constituent variables and for each variable ORIGIN and CLIENT is specified. Accordingly, the variables required for each system of the SOS to find the individual optimal operating point are defined. Also, it is depicted that which systems are related together and have common variables and which systems are completely independent from other systems.

Fig. 7 visualized the relationship table of the envisioned network shown at Fig. 4. In this table LD_CHAR is load characteristics, NET_INFO is network information, PWR_XCHG_MG is power exchanged between DISCO and microgrid, LMP is locational marginal price, RTL_ENR_PRC_D is retail energy price of DISCO, RTL_ENR_PRC_MG is retail energy price of MG, LMT_PWR_XCHG_MG is maximum/minimum limits of power exchanged between DISCO and microgrid, LMT_PWR_XCHG_GRD is maximum/minimum limits of power exchanged between DISCO and upstream grid, BLT_CNT_INFO is bilateral contract information, CAP_CHAR is capacitor bank characteristics, PV_CHAR is PV panel characteristics, WND_SPD is wind speed, CST_GEN is cost curve of power provided by the generators, CPB_CRV_GEN is capability curve of the generators, LMT_PWR_XCHG_DSC is maximum/minimum limits of power exchanged between microgrid and DISCO, MG_OPT is optimal operating point of the microgrid.

As an example, in relationship table of Fig. 7, the MG1 is CLIENT of retail energy price and requests from the DISCO, as the ORIGIN, to send this variable to the MG1. Also, the DISCO is CLIENT of MG operating point and asks the MG1, as the ORIGIN, to send the value of this variable to the DISCO.

B. Operating framework

In order to find the optimal SOS operating point, at first, any microgrid should solve its related optimization problem considering the appropriate optimization constraints. For building the objective function and constraints, each MG, as a CLIENT, requires to get some variables from DISCO. In this paper, $\hat{f}$ implies the dependent variables required by the independent systems to build the optimization model.

The following mixed-integer nonlinear optimization problem is formulated for each MG. In this optimization, the MG is CLIENT of $\hat{\eta}$, $\hat{\beta}$, $\hat{P}_{exD}^{min}$ and $\hat{P}_{exD}^{max}$ which their ORIGIN is the DISCO.

$$
\begin{aligned}
&Max. \quad Benefit = \left((\hat{\eta} \times P_{exD}) \times I_1 + \sum_{i \in load} (\beta_m \times P_{li}) \right) \\
&- \left(\sum_{i \forall dg} Cost(P_{dgi}) + \sum_{i \forall load} (\mu_i \times P_{si}) + (\hat{\beta} \times P_{exD}) \times I_2 \right)
\end{aligned} \tag{1}
$$

where $\hat{\eta}$ is the price that the DISCO purchases energy from the MG, $\hat{\beta}$ is retail energy price by the DISCO, β_m is retail energy price by the MG, and μ_i and P_{si} are cost and amount of i*th* interruptible load submitted by end-use consumers. The optimization constraints are as follows.

1) Load flow equations:

$$P_{gi} - P_{di} = P_i(\theta, V) \quad \forall i \in bus \tag{2}$$

$$Q_{gi} - Q_{di} = Q_i(\theta, V) \quad \forall i \in bus \tag{3}$$

2) Limits of active and reactive power provided by DGs:

$$P_{dgi}^{min} \le P_{dgi} \le P_{dgi}^{max} \quad \forall i \in SDG \tag{4}$$

$$Q_{dgi}^{min} \le Q_{dgi} \le Q_{dgi}^{max} \quad \forall i \in SDG \tag{5}$$

3) Bus voltage limits:

$$V_i^{min} \le V_i \le V_i^{max} \quad \forall i \in bus \tag{6}$$

4) Limit of power flow in the feeders:

$$S_j \le S_j^{max} \quad j \in \text{feeders} \tag{7}$$

5) Load balance constraints:

$$P_{di} = P_{di}^{prim} - P_{si} \tag{8}$$

where P_{di}^{prim} is primarily value of real power consumed by i*th* load, P_{si} is amount of load shedding of i*th* load, and P_{di} is real power demand of i*th* load used in power flow equations.

6) Load shedding restrictions:

$$P_{l_i} \ge P_{cpli} \quad \forall i \in load \tag{9}$$

where P_{cpli} is critical part of the i*th* load.

7) Limits of power exchanged between microgrid and DISCO:

$$\hat{P}_{exD}^{min} \le P_{exD} \le \hat{P}_{exD}^{max} \tag{10}$$

8) Binary variable constraints:

The MG cannot simultaneously play the role of provider and load for the DISCO. The following constraint satisfies this issue.

$$\begin{cases} I_1 \text{ and } I_2 \in \{0,1\} \\ I_1 + I_2 = 1 \\ I_1 \times I_2 = 0 \end{cases} \tag{11}$$

If I_1 is one, the MG sells energy to the DISCO. And if I_2 is one, the MG purchases electricity from the DISCO.

After solving the optimization problem by all MGs, as the autonomous systems, the data requested by the DISCO, as the CLIENT system, are ready to be sent (see Fig.7). Knowing these data and load shedding cost submitted by the interruptible loads, the DISCO solves the following mixed-integer nonlinear optimization problem to maximize its own benefit. In this optimization problem, the DISCO is CLIENT of $\hat{I}_{1i}$, $\hat{I}_{2i}$, $\hat{P}_{exDi}^{sch}$ and $\hat{P}_{exDi}^{sch}$ variables which their ORIGINs are the MGs.

$$Max. \quad Benefit = \left(\begin{array}{l} \sum_{i \in load} (\beta \times P_{li}) + \left(\sum_{i \in MG} (\beta \times |P_{exDi}|) \times \hat{I}_{2i} \right) \\ + (\lambda \times P_{exB}) \times J_1 \end{array} \right)$$
$$- \left(\left(\sum_{i \in MG} (\eta \times P_{exDi}) \times \hat{I}_{1i} \right) + (\lambda \times P_{exB}) \times J_2 + \sum_{i \in load} (\mu_i \times P_{si}) \right) \tag{12}$$

where λ is locational marginal price (LMP) and μ_i is cost of i*th* interruptible load submitted by end-use consumers. The constraints (2), (3) and (6)-(9), as well as the following constraints must be considered in this optimization problem.

1) Injected power by the MGs:

According to the relationship table, the MGs must send their scheduled exchanging power with the upstream grid to the DISCO. These scheduled values for P_{exD} must stay fixed when the DISCO aims to maximize its own profit.

$$P_{exDi} = \hat{P}_{exDi}^{sch} \qquad \forall i \in MG \tag{12}$$

This value can be positive or negative. The positive value means that the MG provides electricity for the DISCO and the negative value indicates that the MG plays the role of a load for the DISCO.

2) Voltage constraints at the MGs terminal:

In order to avoid the variation in MGs operating point, the voltage of point of common coupling (PCC) between DISCO and MG must stay at the scheduled value defined by the MG.

$$V_{pcci} = \hat{V}_{pcci}^{sch} \quad \forall i \in MG \tag{13}$$

3) Limits of power exchanged between distribution grid and bulk power system:

$$P_{exB}^{min} \le P_{exB} \le P_{exB}^{max} \tag{14}$$

4) Binary variable constraints:

The DISCO cannot simultaneously play the role of provider and load for the bulk power system. The following constraint satisfies this issue.

$$\begin{cases} J_1 \text{ and } J_2 \in \{0,1\} \\ J_1 + J_2 = 1 \\ J_1 \times J_2 = 0 \end{cases} \tag{15}$$

If J_1 is one, the DISCO sells energy to the wholesale electricity market. And if J_2 is one, the DISCO purchases electricity from the wholesale electricity market.

IV. Numerical Results

In this section, the SOS framework is applied on the distribution grid shown in Fig.4. The resistance and reactance of all lines are equal to 0.1 and 0.15, respectively. The locational marginal price is equal to 3$/MW. Retail energy price by the MG, β_m, is 20$/MW. The power provided by PV panel and wind turbine MG2 and 3 are assumed to be 250 and 300KW, respectively. We have classified MG1 as system 1, MG2 as system 2, MG 3 as system 3, and DISCO as system 4. Table I depicts cost curve of the DGs located in the systems.

Table I
Cost Curve of the DGs

System	DG Number	Cost curve		
		a	b	c
System 1	1	0.09	5.5	13
	2	0.07	5.2	9
	3	0.08	5.8	11
System 2	1	0.03	2.3	8
	2	0.04	2.1	7
System 3	1	0.03	2.1	8

$Cost(p) = c + b * P + a * P^2$

At first, each system requires getting the value of variables which must be known for solving the appropriate optimization problem to find the optimal operating point of the system. Table II presents the known and unknown variables which we have at the beginning process of the optimization problem.

Table II

ORIGIN AND CLIENT OF KNOWN AND UNKNOWN VARIABLES

Known			Unknown		
Variable	ORIGIN	CLIENT	Variable	ORIGIN	CLIENT
$\hat{\beta}$ =5$/MW	DISCO	MGi	$\hat{P}_{exDi}^{sch}$ =?	MGi	DISCO
$\hat{\eta}$ = 3$/MW	DISCO	MGi	$\hat{P}_{exDi}^{sch}$ =?	MGi	DISCO
$\hat{P}_{exD}^{min}$ = -10MW	DISCO	MGi	$\hat{I}_{1i}$ =?	MGi	DISCO
$\hat{P}_{exD}^{max}$ = 10MW	DISCO	MGi	$\hat{I}_{2i}$ =?	MGi	DISCO

According to Table II, the variables which the DISCO is their ORIGIN are known and the variables which the MGs are their ORIGIN are unknown. On the other words, as the CLIENT, each MG knows all required variables to solve its appropriate optimization problem. Thus, using the sequential quadratic programming, the optimization problem for each MG is solved and the results are presented in Table III.

TABLE III
OPTIMAL OPERATING POINT OF THE MGS

MG Number	Benefit ($)	DG Number	P_{dg} (MW)	Q_{dg} (MW)
One	39.27	1	0.000	-0.014
		2	0.479	0.138
		3	0.000	0.200
Two	5.54	1	0.800	0.096
		2	0.806	0.108
three	5.11	1	0.696	0.011

Now, the unknown variables shown in Table II, which are required to solve the optimization problem by DISCO, are available. As the ORIGINs, the MGs send these variables to the CLIENT which is DISCO. Table IV shows these variables ($\hat{P}_{exDi}^{sch}$, $\hat{V}_{pcci}^{sch}$, $\hat{I}_{1i}$ and $\hat{I}_{2i}$) and their values. It should be noted that when $\hat{I}_{1i}$ is one and $\hat{I}_{2i}$ is zero, MG_i supplies electricity for the DISCO, and when $\hat{I}_{1i}$ is zero and $\hat{I}_{2i}$ is one, DISCO provides electricity for MG_i. Positive value for $\hat{P}_{exDi}^{sch}$ means that the MG is purchasing power from the DISCO, and the negative value implies that the MG is selling energy to the DISCO.

TABLE IV
VARIABLES SENT BY MGS AS THE ORIGIN TO DISCO AS THE CLIENT

MG Number	$\hat{P}_{exDi}^{sch}$ (MW)	$\hat{V}_{pcci}^{sch}$ (pu)	$\hat{I}_{1i}$	$\hat{I}_{2i}$
One	0.762	1.050	0	1
Two	-0.038	0.950	1	0
three	0.473	0.991	0	1

Receiving the variables shown in Table IV, the DISCO formulates the appropriate optimization problem to maximize its own benefit. In this formulation, the 30% of the loads is assumed as the interruptible load which its cost is 15$/MW. Table V presents the results of optimization problem solved by DISCO. According to the result, the DISCO defines the optimal value of energy which should be purchased/sold from/to the wholesale electricity market.

TABLE V
OPTIMAL OPERATING POINT OF THE DISCO

Benefit of power sold to the loads ($)	13.48
Cost of load shedding ($)	0.00
Net benefit ($)	5.07
P_{exB} **(MW)**	2.805

Now, using the proposed SOS framework, the optimal operating points of three MGs as well as the optimal operating point of DISCO, as the independent system, are obtained. Consequently, the optimal operating point of the distribution grid, as the SOS, is defined.

V. CONCLUSION

This paper presents a system of systems framework to find the optimal operating point of the active distribution grids. This framework regards the distribution companies, microgrids and end-use customers as the self-governing systems which are autonomously managed and operated. All independent entities aim at increasing their own benefit while they work together to guarantee secure and reliable operation of the distribution grid as the system of systems. In order to show the data flow information and clarify the process of transferring data between the independent systems, a relationship table is presented. Also, based on this relationship table, the sequences of the optimization problems for the entities are defined. This framework is carried out on a typical distribution grid with suitable and proficient performance.

VI. REFERENCES

[1] M. Shahidehpour, H. Yamin, Z. Li, *Market operation in electric power systems*, New York: Wiley, 2002.
[2] A. Kargarian, M. Raoofat, "Stochastic reactive power market with volatility of wind power considering voltage security," *Energy*, vol. 36, pp. 2565-2571, 2011.
[3] R. Palma-Behnke, J.L. Cerda, L.S. Vargas, A. Jofré, "A distribution company energy acquisition market model with integration of distributed generation and load curtailment options," *IEEE Trans. Power Syst.*, vol. 20, no. 4, pp. 1718-1727, Nov. 2005.
[4] S.P. Chowdhury, P. Crossley S. Chowdhury, *Microgrids and active distribution networks*, Institution of Engineering and Technology, July 2009.
[5] M.H. Bollen, F. Hassan, *Integration of distributed generation in the power system*, Wiley, John & Sons, 2011.
[6] C.H. Ng, T.T. Lie, L. Goel, "Impact of distributed generation on system reliability in competitive electricity markets," International Conference of Power Engineering, IPEC, pp. 735-740, Dec. 2007.
[7] J.M. Held, "The modeling of systems of systems," PhD Thesis, University of Sydney, 2008.
[8] R.H. Lasseter, Microgrids, In: Proceedings of the IEEE Power Engineering Society Winter Meeting, vol. 1, January, 2002, pp. 305–308.
[9] W. El-Khattam, K. Bhattacharya, Y. Hegazy, M.M.A. Salama, "Optimal Investment Planning for Distributed Generation in a Competitive Electricity Market," IEEE Trans. Power Syst., vol. 19, no. 3, pp. 1674-1684, Aug. 2004.
[10] R.A. Wolf, "Multiobjective collaborative optimization of system of systems," M.Sc. Thesis, Massachusetts Institute of Technology, 2005.
[11] M. Jamshidi, *System of systems engineering: innovations for the 21th century*, Wiley, 1 edition, 2008.