Multi-objective Smart Distribution Network Operation considering Demand Response Programming

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I. Introduction

While societies are becoming more progressed and industrialized, the need for energy increases day by day. On the other hand, household energy consumption share, in comparison to the total consumption increases the demand prediction error [1], [2]. This unpredictability makes fossil fuels to be the primary source of energy, which causes to the increase of greenhouse gases emission and many more issues[3]. Moreover, another significant problem of the current power grid is the long distances between the generation of consumption sides leading to significant energy loss in transmission lines and instability of the networks [4]–[6]. On the other hand, traditional distribution networks makes the transmission grid vulnerable to the blackouts since transmission grids are their only source of energy. One of the leading solutions to overcome these defects is using Distributed Energy Resources (DER), while the most efficient method to manage these resources is organizing them under smart grids networks [7], [8].

Smart grids make bi-directional energy and information transmission possible [9]–[11]. These grids can contain smart generation units, substations, distribution, transmission terminals, planning units, houses, measurements, and storage systems [6], [12], [13]. One of the key technologies in smart girds is Demand Side Management (DSM) [14]. The main objective of DSM is the optimal management of energy resources and end-user experiences [15]–[17].

In traditional power systems, only generation side management could be used for controlling the power systems. However, discussions about using DR for load management been present back then. However, these discussions has been put aside after reformation of power systems and incompatibility of DR with market rules [18]. However, those programs had been restructured to be compatible with modern power systems. After the reformation of power systems, the DR programs constitute a considerable portion of load management programs. Since, the nature of these programs is very compatible with the new structure of power system networks. Today, The DR is proposed to solve many of power systems network issues such as load peak curtailment in Distributed System Operation (DSO) or optimizing the power generation of Distributed Generations (DG). It can balance the internal assets and stocks of retailers. It can optimize the day/hour ahead market and control the frequency and system reserves [19], [20].

In this work, we provide a model to optimize the operation of a smart grid. The proposed model as formulated as a day ahead operation problem. Based on the proposed model, owner of grid can reach the goals such as:

- reducing network loss, reducing the cost of purchasing power from the upstream networks.
- Incorporating demand side management.
- RES such as wind turbine and PV will be incorporated into this model alongside of the dispatchable resources.

The proposed model which is formulated as an optimization problem will be solved using GAMS software.

II. Problem Formulation

A. Cost Function

The proposed model is defined as a multi-objective optimization problem. The first part of the cost function minimizes economical cost which itself has two sections: 1) the cost of buying energy from upper hand grid. 2) the cost of electric loss in the network. The second part of the objective minimizes the voltage deviation of busses in the grid.

1) First Cost Function

As mentioned before, this section aims to minimize the energy purchase cost and electric loss in the grid which is obtained from (1).

$$CostPG = \sum_{t=1}^{24} E_{price}(t) \times \Big(\sum_{i=1}^{n} [P_{Di}(t) - P_{Gi}(t)] + P_{Loss}(t)\Big) \quad (1)$$

In the above equation, $\boldsymbol{E_{price}(t)}$ is the electricity cost which is known in the day-ahead market. The $P_{Loss}(t)$, $P_{Di}(t)$ and $P_{Gi}(t)$ are the total energy loss in the grid, the load of bus *i* at time *t*, and the energy generation of DER of bus *i* at time *t*, respectively. The second part of first objective function is the electric network losses which is calculated by (2):

$$CostPLoss = E_{PLoss} \times \sum_{t=1}^{24}\sum_{i=1}^{n}(P_{Gi}(t) - P_{Di}(t) - \sum_{j\in M} V_j(t)V_i(t)Y_{ij}cos(\delta_j(t) - \delta_i(t) - \theta_{ij})) \quad (2)$$

In the above equation, the $P_{Gi}(t)$ and $P_{Di}(t)$ are generated and consumed power of bus *i* respectively. Also, $V_i(t)$ and $\delta_i(t)$ are the voltage magnitude and phase of bus *i*, respectively. The Y_{ij} , θ_{ij} are the magnitude and phase of admittance between bus *i* and *j*, receptively. The E_{PLoss} unit is per *kWh* cost of electric losses in the grid. Finally, the first part of cost function would be:

$$OF_1 = CostPG + CostPLoss \quad (3)$$

2) Second cost Function

As mentioned before, the second part is related to improving the power quality in the grid. One of the metrics of power quality is keeping the voltage at buses in the acceptable range. Therefore, the second part of cost function is defined as deviation of buses voltage from the desired value which is defined as (4):

$$OF_2 = \sum_t\sum_i |V_i(t) - V_n| \quad (4)$$

3) Dual-objective Cost Function

The final cost function of the proposed problem is defined as (5) by using Weighted Sum Method (WSM). In which, the ω_1 and ω_2 are the weights of functions OF_1 and OF_2 , respectively. The OF_{1min} and OF_{2min} are their minimum value which is obtained by solving each of them separately.

$$OF = \omega_1 \frac{OF_1}{OF_{1min}} + \omega_2 \frac{OF_2}{OF_{2min}} \quad (5)$$

$$\omega_1 + \omega_2 = 1 \quad (6)$$

B. Constraints

In this section the constraints of the problem will be explained. They are modeled as equality and inequality of linear and non-linear constraints. They simulate different sections of the simulated system such as distributed network, wind turbine, PV, and the demand response in the grid.

1) Model of the Distribution Network

In this work, the AC current model is used to model the network. In this section, the equations of AC load dispatch will be introduced. (7) and (8) show the active and reactive power at bus *i*. Also, the power balance at bus *i* is shown in (9) and (10), and (11) to (13) show the constraints on buses voltage, active and reactive power of DERs, respectively.

$$P_i^{cal,e} = \sum_{j=1}^{N_e}|V_i||V_j|(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \quad (7)$$

$$Q_i^{cal,e} = \sum_{j=1}^{N_e}|V_i||V_j|(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \quad (8)$$

$$P_i^{gen,e} = P_i^{dem,e} + P_i^{cal,e} \quad (9)$$

$$Q_i^{gen,e} = Q_i^{dem,e} + Q_i^{cal,e} \quad (10)$$

$$V_{i,min} \le V_i \le V_{i,max} \quad (11)$$

$$P_{i,min}^{gen,e} \le P_i^{gen,e} \le P_{i,max}^{gen,e} \quad (12)$$

$$Q_{i,min}^{gen,e} \le Q_i^{gen,e} \le Q_{i,max}^{gen,e} \quad (13)$$

Also, (14) to (16) show the active, reactive, and real power flow in transmission lines. (17) shows the thermal constraint on transmission lines.

$$P_{line\_ij}(t) = V_j(t)V_i(t)Y_{ij}cos(\delta_j(t) - \delta_i(t) - \theta_{ij}) \quad (14)$$

$$Q_{line\_ij}(t) = V_j(t)V_i(t)Y_{ij}sin(\delta_j(t) - \delta_i(t) - \theta_{ij}) \quad (15)$$

$$S^2{}_{line\_ij}(t) = P^2{}_{line\_ij}(t) + Q^2{}_{line\_ij}(t) \quad (16)$$

$$\underline{S}_{line\_ij}(t) \le S_{line\_ij}(t) \le \overline{S}_{line\_ij}(t) \quad (17)$$

2) Wind Turbine Model

The wind turbines turn the kinetic energy of wind to mechanic energy and then from mechanical energy to electrical energy. generally, the generated power is dependent to air density, wind speed blades size, and wind energy efficiency:

$$P_{WT} = \frac{1}{2}\varphi.\pi.R_{(WT)}^2.V^3.C_P \quad (18)$$

Where P_{WT} show the generated energy by the wind turbine, φ shows the air density, *V* represent the wind speed, R_{WT} show the radius of blades and *Cp* is for the efficiency of energy transformation. When the position of turbine and its type is determined, the air density and blade radius could be considered constant. Therefore, based on the test performed on a turbine, one can obtain the actual relationship between generated power and wind speed which could be shown as a constraint:

$$P_{WT} = 0\,, \qquad V < V_{ci} \quad (19)$$

$$P_{WT} = aV^3 + bV^2 + cV + d\,, \qquad V_{ci} < V < V_r \quad (20)$$

$$P_{WT} = P_r\,, \qquad V_r < V < V_{co} \quad (21)$$

$$P_{WT} = 0\,, \qquad V_{co} < V \quad (22)$$

In above equations, the P_r, V_r, V_{ci} and V_{co} are rated power, rated speed, minimum speed and maximum speed respectively. The studied wind turbine model is AOC 15/50 and it's parameter according to [35] are:

$V_{ci} = 5.26\ m/s$ ، $V_r = 14.68\ m/s$ ، $V_{co} = 22.40\ m/s$ ، $P_r = 50\ kw$

$d = 16.3773$ ، $C = -10.8347$ ، $b = 1.7882$ ، $a = -0.0609$

3) Photovoltaic Array Model

Photovoltaic array is a set of solar panels that are connected together. Each module can't provide enough power. that is why they are connected in arrays. If these panels does not have any moving component, they will not create any greenhouse gases and are usually low maintenance. PV arrays output power is obtained through the following equation:

$$P_{pv} = P_{STC} G_{ING}/G_{STC}(1 + K(T_c - T_r)) \quad (23)$$

In above equation, P_{pv}, P_{STC} and T_r are the output power of each module, maximum output power, reference temperature, and ambient temperature respectively. The K is the ratio between output power and the temperature. Based on [35], the values that are used in this work are:

$T_r = 0 \qquad P_{STC} = 25\ kw \qquad G_{STC} = 1000\ W/m^2$

$K = 0.0167$

4) Demand Response Model

In this work, the main objective of DR program is to shift the demand from peak hours to the off-peak hours. Based on different management policies, different DR programs have been proposed. In this work, a model based on Time-of-Use (ToU) is presented. Equation (24) and (25) show that the network can only move a portion of the loads to other times. Equation (26) is a constraint on maximum allowed transferable electric load. equation (27) and (28) shows the deviation percentage of electric load. equation (29) shows the total amount of reduction of loads during operation time, must be equal to the total amount of increased load at other times [36].

$$Load_h(t) = (1 - DR_h(t))L_h(t) + sdr_h(t) \quad (24)$$

$$L_h(t) - Load_h(t) = DR_h(t)L_h(t) - sdr_h(t) \quad (25)$$

$$Load_h^{inc}(t) \le inc_h(t) \times L_h(t) \quad (26)$$

$$DR_h(t) \le DR_h^{max} \quad (27)$$

$$inc_h(t) \le inc_h^{max} \quad (28)$$

$$\sum_{t=1}^{24} sdr_h(t) = \sum_{t=1}^{24} DR_h(t) \times L_h(t) \quad (29)$$

III. Simulation Results

In this paper, IEEE 33 bus test network is carried out as case study test system. In which, a 50 KWh AOC 15/50 wind turbine and a PV array with 25 KWh of rated power are installed at buses 30 and 25, respectively. Also, a diesel generator with rated power of 100 KWh is installed at bus 24. The following section discusses about the smart grid test system in more details.

A. Case Study

As mentioned before, the IEEE 33 bus grid, based on [37], is applied as test case for analyzing the proposed model. It consists of 1 substation feeder, 33 buses, 35 transmission lines. Respectively, the base voltage and base power are considered 12.66 kV and 10 MVA. To generate the hourly load based on the base load (*BL*) of the grid, the following equation has been used:

$$P_{Di}(t) = LF(t) \times BL_i \quad (30)$$

Where, $LF(t)$ is load factor for each hour, which it is illustrated in Fig. 1. In this figure, three load levels include the light, medium, and heavy load levels are considered that they belong for the hours 1 am - 10 am, 11 am - 6 pm, and 7 pm - 12 pm, respectively. Also, the costs of the buying energy from the upstream network are 0.028, 0.049, 0.087 $kwh for each level of load, respectively.

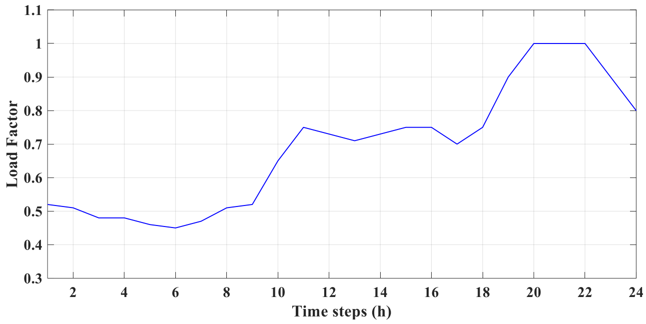

Fig. 1. Load factor curve for the grid in the different hours

B. Results and discussion

To evaluate the effectiveness of the proposed model, three different scenarios is considered in this paper. Also, two different case are considered for each scenario. In the first case, network operation is done based on day-ahead operation without implementing DR. In the second case, DR programing is implemented to operate the network. These three scenarios, which are considered in this paper, are as follows:

1- Single objective model by considering the first cost function of the proposed problem as the objective of optimization.

2- Single objective model by considering the second cost function of the proposed problem as the objective of optimization.

3- Multi-objective model by considering both of the cost functions of the proposed problem.

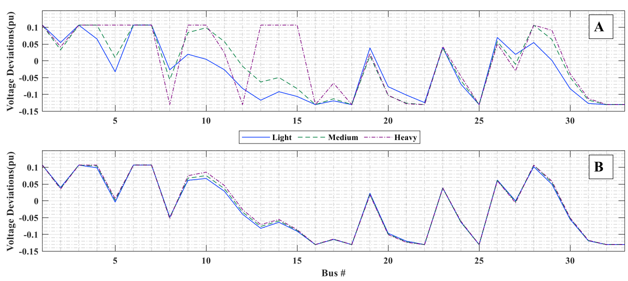

Fig. 2. Voltage deviations for Senario 1; Case 1 (A), Case 2 (B)

Fig. 2 shows the obtained results related to the voltage deviation of the network in three different load levels for scenario 1. The total deviation from the nominal voltage for each of the intervals is equal to 32.26, 33.68, and 38.29, respectively. Also, the obtained results related to the voltage deviation for scenario 2 and 3 are illustrated in Fig. 3 and 4. As can be seen, the lowest deviation belongs to scenario 2 of case 2. For better demonstration, the total voltage deviations for different scenarios are provided in table 1.

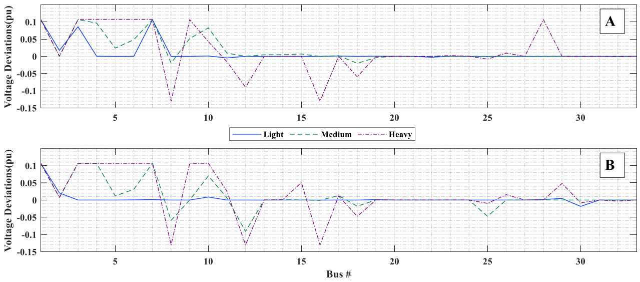

Fig. 3. Voltage deviations for Senario 2; Case 1 (A), Case 2 (B)

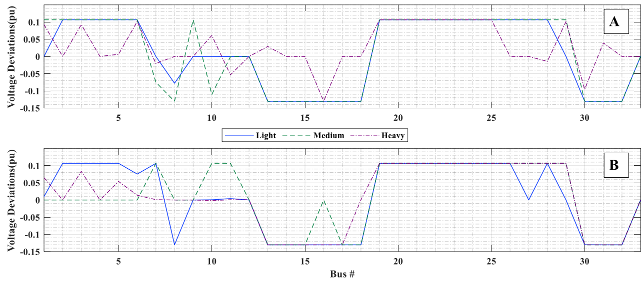

Fig. 4. Voltage deviations for Senario 3; Case 1 (A), Case 2 (B)

Table 1. The obtiand results of the total voltage deviation

Scenario Number	Total Voltage Deviation (pu)	
	Case 1	**Case 2**
S1	65.73	64.32
S2	64.92	63.87
S3	65.24	64.02

Table 2. The obtiand results of the total power losses of SDN

Scenario Number	Total Power Losses (MW)	
	Case 1	**Case 2**
S1	2.1336	1.9548
S2	3.5029	3.4514
S3	2.3138	2.0119

The obtained results of the total power for different scenarios of the cases are listed in table 2. From economical point of view, we can see the best results has been obtained for scenarios 1 of case 2. However, this scenario has the worst power quality in comparison to the other two scenarios for case 2. The reason is that it only tries to optimize economical metrics. Therefore, the results illustrate well the proposed problem performance based on different operational goals and it can be concluded the operator of the system can reach the optimal economic or optimal quality points considering each of these goals as the objective function of the proposed problem. Nevertheless, when both of these goals are important for the system operator simultaneously, the objective function should be considered as a multi-objective optimization problem in order to achieve a trade-off solution.

Fig. 5 demonstrates the purchased power from upstream network for the scenario 3 of case 1 and 2. As it can be seen, the demand for purchasing power from upstream network is reduced the hours with expensive electricity price and shifted to the hours with cheap electricity price by implementing DR program. Fig. 6 shows the total load of the grid before and after the DR programing (case1 and case2). The dashed line represents the traditional grid load consumption and the solid line represent the smart grid load consumption with DR. As it can be seen, by implementing DR program into this system, the load consumption shifted from peak hours to light load hours of the grid.

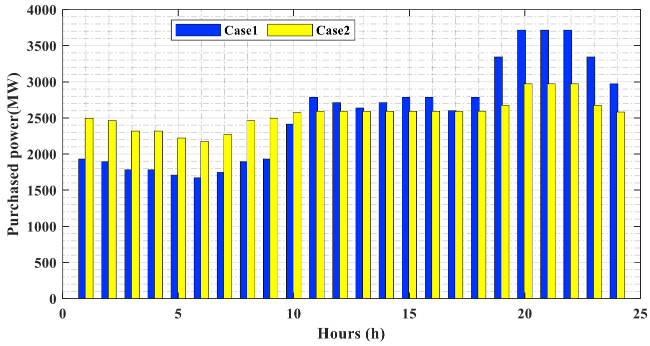

Fig. 5. Purchased power from upstream network

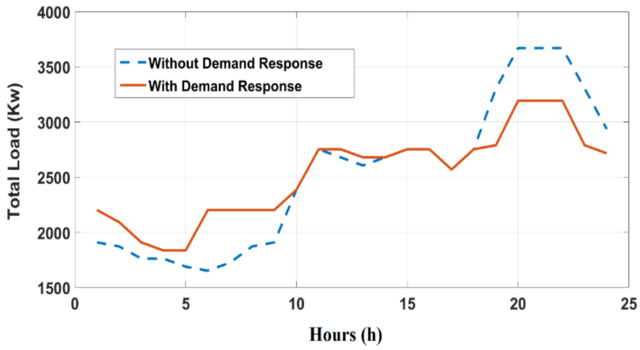

Fig. 6. The total load of the grid before and after the DR programing

IV. Conclusion

Smart grids are a new trend to improve the operation and performance of distributed network by utilizing advanced technologies. They provide a bi-directional communication platform between generation and consumption. This ability provides a platform that energy consumption occurs in an optimal manner. In this work, a multi-objective optimization model based on day-ahead scheduling to control a smart distribution network is provided in order to minimize the operation cost and maximize the power quality of the network. By comparing the results of the two cases, it has been seen that the proposed model (case2) has resulted better than the traditional model (case1) for all of the proposed scenarios. Also, scenarios 1 and 2 result in the optimal quality point and optimal economic point, respectively. While scenario 3 gives a trade-off solution considering both economical and quality goals.

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