21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE US National Committee
2022 Grid of the Future Symposium

Effective Microgrid Optimal Dispatch Settings

M. FARAJOLLAHI, A. MOJALLAL, M. R. DADASH ZADEH
ETAP
USA

SUMMARY

Active power control is one of the crucial functions run by the microgrid controller to schedule distributed energy resources (DER) in a microgrid. This schedule can be obtained through solving an optimization problem, so-called optimal dispatch, to minimize the cost of microgrid operation. To match all possible cases that can occur during real-time operation as well as to ensure that the optimal dispatch always reaches a feasible solution, some of the constraints associated with optimal dispatch problem are defined in terms of soft constraints, which introduces penalty factors into the problem. The user needs to tune these penalty factors, which might be confusing and cumbersome. In this regard, there is a considerable value in easing the hassle of tuning penalty factors. This paper first proposes a method to reduce the number of penalty factors used in the microgrid optimal dispatch problem. Additionally, the penalty factors are introduced in such a form that users can easily tune them all together with minimum effort.

KEYWORDS

Microgrid, Optimal Dispatch, Penalty Factor.

mohammad.farajollahi@etap.com

I. INTRODUCTION

A microgrid is defined as a collection of distributed energy resources (DERs) and loads that act as a single controllable entity with respect to the grid and can operate in both grid-connected and islanded modes [1]. In many microgrids, energy storage systems are mainly used to enable operation in islanded mode. The presence of energy storage systems provides a great opportunity to achieve peak shaving, reduce emission in power consumption, enhance grid stability, etc. In grid-connected mode, the energy storage systems can facilitate the integration of renewable energy resources by controlling the microgrid exchanging power to the gird. On the other hand, the standalone operation of the microgrid increases customers' reliability by reducing their susceptibility to grid disturbances and increases the grid resiliency in response to potentially disruptive events.

Although the combination of renewable sources and energy storage systems within microgrids is very beneficial, as mentioned above, managing and controlling of DERs in a microgrid can bring up many challenges, which requires a microgrid control system. This system can determine dispatchable quantities of DERs based on various possible objectives and constraints. In a typical microgrid control system configuration, each microgrid DER (or a combination of them) needs a local/primary controller to monitor and meet dispatch values determined by the microgrid controller. At a secondary control level, a microgrid controller is required to continuously monitor the microgrid DERs and loads, calculate optimal setpoints based on real-time measurements and send the new commands to DERs and loads [2]. In this regard, the microgrid controller is responsible for coordinating among the microgrid assets through running several functions such as active power control, planned islanding, unplanned islanding, reactive power control, black start, and reconnect [3].

In the grid-connected mode, the active power control function is mainly responsible for dispatching DERs to limit export power to the grid in case of an excess of renewable generation by charging energy storage. The stored energy should also get a chance, preferably at the time of high import power from the grid, to discharge and to perform peak shaving while opening room for the next charging opportunity [4]. In the islanded mode, this function is responsible to dispatch DERs to maintain reserve margin in grid-forming DER(s) as well as maintaining stored energy for the expected islanded operation time duration [5].

The active power control function can be implemented based on solving an optimization problem to determine the optimal set-points of DERs. This problem tries to schedule the optimal generation of the DERs over a time horizon according to the forecasted active power of loads and renewable sources, as well as accounting for operational constraints, such as fuel costs, the state of charge mode, and energy import/export costs, exchange power limits to the grid, etc. [6].

Microgrid optimal dispatch problem requires many parameters to be set by users. Within these settings, penalty factors are a set of parameters that are used for two purposes. First, they are used to convert hard constraints to soft ones. One example is to address some rare but possible constraint violations in real-time operation, e.g., the energy storage state of charge violation [7]. Second, penalty factors are used to penalize or incentivize a certain variable within the objective function, such as penalizing load shedding to be used as the last resort. This approach also guarantees the solution of the optimization problem in all conditions. As will be discussed in this paper, the penalty factors need to be tuned carefully for proper scheduling of generation in the microgrid. The process of tuning penalty factors needs a knowledgeable user both in optimization and power system, which requires a substantial training process for the user to become familiar with the penalty factors and their purposes in the optimal dispatch problem. In this regard, it is substantially beneficial to facilitate the tunning process of the penalty factors for the user. In this paper, we propose three useful strategies that can ease tunning of the penalty factors. On the one hand, these strategies can minimize the efforts for tunning the penalty factors. On the other hand, it would enhance the proper selection of the penalty factors to avoid any mis-operation in the microgrid.

II. PROBLEM DEFINITION

Cost effective scheduling of DERs along with considering operational limitations in the microgrid needs a multi-interval optimization process. This section represents objective function as well as the constraints of the optimal dispatch problem.

A. Cost Fucntion

The main objective of the optimal dispatch problem is to schedule the microgrid assets in order to achieve the minimum cost. This cost function can be expressed as follows:

$$Costs = \sum_{t=1}^{\mathcal{N}_T} C^{Ex}[t] + C^G[t] + C^S[t], \quad (1)$$

where at time section t, $C^{Ex}[t]$ is the cost associated with exchanged power with the grid. Also, $C^S[t]$ and $C^G[t]$ represent the operation cost of the energy storages and the generators.

B. Hard Constraints

There are plenty of operational considerations in microgrid operation which are necessary to guarantee the proper operation of microgrid upon scheduling the DERs. In this regard, several constraints related to operation of a microgrid and individual assets are introduced in optimal dispatch problem which are firm and cannot be violated. These constraints are called "hard constraints" and explained as follows [6]:

- **Power Balance**: in each energy time section, the balance between generation and load should be maintained in microgrid.
- **Storage Energy Balance**: this constraint dictates how storage SOC should be evolved over time, depending upon the storage charging/discharging powers, efficiencies, and standby loss.
- **Storage Simultaneous Charge/Discharge**: this constraint ensures that the storage is either in charge or discharge mode.
- **Storage Initial State**: the initial SOC information of the storage should be passed to the optimal dispatch problem.
- **Storage Sustainability**: this constraint ensures that storage is operated with a constant cycle over the prediction horizon.

C. Soft Constraints

Depending on the microgrid conditions and configurations, some constraints, so-called soft constraints, are not firm and can be violated. From the operational perspective, these violations are undesired and should be avoided unless they are necessary to match all possible cases that can occur during operation and to guarantee a feasible solution for the optimization problem. Therefore, in case any constraint is violated, the violation should be reflected as a cost to the objective function. So, the objective function of the optimal dispatch problem can be defined as:

$$Objective = Costs + Penalties, \quad (2)$$

where, $Penalties$ is the total of penalties that are related to violated constraints. Note that the $Penalties$ should have the same unit as $Costs$. Therefore, a "penalty factor" parameter is used to make a penalty related to a constraint compatible with the cost function. As the goal of optimal dispatch problem is to minimize the $Objective$, it is tried to reduce the penalties as much as possible. Therefore, the optimization problem ensures that the violations are necessary. Several of important soft constraints are explained as below:

DER Power Limits: the power of a DER should be kept within an operational range defined by maximum and minimum acceptable power. However, this maximum and minimum value of power may need to be violated. For example, assume that there is an excessive generation in a microgrid and a diesel generator is running at its minimum power. In that case, the diesel generator should produce less than its defined minimum power to reach a feasible solution. Therefore, the DER power limit can be expressed in form of a soft constraint as follows:

$$P_i^{DER}[t] \leq P_i^{DER-Max} + P_i^{Violate+}[t], i \in \mathcal{N}_{DER}, \quad (3)$$

$$P_i^{DER}[t] \geq P_i^{DER-Min} - P_i^{Violate-}[t], i \in \mathcal{N}_{DER},$$

where at time step [t], $P_i^{DER}[t]$ is the power variable associated with DER i, $P_i^{DER-Min}$ and $P_i^{DER-Max}$ are the desired lower and upper limits for $P_i^{DER}[t]$, and $P_i^{Violate-}[t]$ and $P_i^{Violate+}[t]$ are the violation variables associated with DER i power limit. $P_i^{Violate+}[t]$ and $P_i^{Violate-}[t]$ can be reflected as a penalty in objective function using $PF_i^{Violate-}$ and $PF_i^{Violate+}$ for $i \in \mathcal{N}_{DER}$.

Load Power: the value of loads power over the optimization horizon are provided through forecasting. However, the loads power may differ from their forecasted value. For instance, in lack of enough generation, some loads need to be shed to meet the power balance. The load power constraint is presented as:

$$P_i^L[t] = P_i^{LF}[t] - P_i^{Shed}[t], i \in \mathcal{N}_L, \quad (4)$$

where at time step $[t]$, $P_i^L[t]$ is the variable associated with power of load i, $P_i^{LF}[t]$ is the forecasted value of load power, and P_i^{Shed} is the variable associated with the amount of load which needs to be shed. $P_i^{Shed}[t]$ can be reflected as a penalty into the objective function using PF_i^{Shed} for $i \in \mathcal{N}_L$.

Renewable Power: similar to loads, the value of renewable resources power over the optimization horizon are provided through the forecasting. In some situations, however, renewable resources cannot generate at their forecasted value. Assume that the exporting power from microgrid is not allowed and the amount of generated power by renewable resources is greater than the total loads power. In this case, it is necessary to curtail some amount of renewable resources power in order to maintain the generation and consumption power balance in the microgrid. Therefore, the power of renewable resources in optimal dispatch problem is presented as:

$$P_i^R[t] = P_i^{RF}[t] - P_i^{Curtail}[t], i \in \mathcal{N}_R, \quad (5)$$

where at time step $[t]$, $P_i^R[t]$ is the power variable associated with renewable resource i, $P_i^{RF}[t]$ is the forecasted power value of renewable resource i, and $P_i^{Curtail}[t]$ is the amount of power which needs to be curtailed. The range of $P_i^{Curtail}[t]$ can also be defined through an additional hard constraint to limit the amount of power curtailment. $P_i^{Curtail}[t]$ can be reflected as a penalty into the objective function using $PF_i^{Curtail}$ for $i \in \mathcal{N}_R$.

Storage State-of-Charge: state-of-charge (SOC) of storage should be kept within an operational range defined by maximum and minimum acceptable SOC. However, there are some inevitable situations that SOC needs to be set out of the desired range. For instance, if the initial SOC of the storage is below the minimum or above the maximum, the SOC constraint needs to be violated. Hence, the SOC constraint is also formulated as a soft constrain:

$$SOC_i[t] \geq SOC_i^{Min} - SOC_i^{Violate-}[t], i \in \mathcal{N}_S, \quad (6)$$

$$SOC_i[t] \leq SOC_i^{Max} + SOC_i^{Violate+}[t], \ i \in \mathcal{N}_S,$$

where at time step [t], $SOC_i[t]$ is the SOC of storage i, SOC_i^{Min} and SOC_i^{Max} are the desired lower and upper and limits for $SOC_i[t]$, and $SOC_i^{Violate-}[t]$ and $SOC_i^{Violate+}[t]$ are the violation SOC variables associated with storage i. $SOC_i^{Violate+}[t]$ and $SOC_i^{Violate-}[t]$ can be reflected as a penalty into the objective function using PF_i^{SOC} for $i \in \mathcal{N}_S$.

Smooth Operation of Storage: due to the fast-response requirements of storage inverters to respond to the huge loads changes in short time in the microgrid, usually the ramp rate constraints and shutdown and startup costs can be ignored for storages in scale of optimal dispatch time steps. However, this relaxation may results in the huge fluctuation in the scheduled generation of storages. In this regard, a set of constraints for smooth operation of storages are introduced as follows:

$$-P_i^{Smooth}[t] \leq P_i^S[t] - P_i^S[t-1] \leq P_i^S[t], i \in \mathcal{N}_S, \quad (7)$$

where, $P_i^S[t]$ is the power variable of storage i, $P_i^{Smooth}[t]$ is difference between powers at time step t and $t-1$ that acts as the controlling variable to limit the difference of power at two consecutive time steps. $P_i^{Smooth}[t]$ can be reflected as a penalty into the objective function using PF_i^{Smooth} for $i \in \mathcal{N}_S$.

III. Proposed Solution

As discussed in section II.C, several soft constraints are introduced in the microgrid optimal dispatch problem to ensure that a feasible solution is achieved. Although introducing these soft constrains guarantees the feasibility of the solution and desired dispatch setpoints, it increases the number of variables in the optimization problem, thereby making the problem more complex to be solved. More importantly, each of these soft constraints needs a penalty factor to convert the associated value of the constraint to a cost in the objective function. It is very important to select the correct values for penalty factors to avoid undesired violation among possible violations, otherwise desired and logical dispatch setpoints will not be achieved.

In a practical world, typical user does not have sufficient knowledge, time, and tools to study and tune all these penalty factors together to reach an effective and optimal feasible solution. Therefore, it is of great value to tune all the penalty factors automatically and efficiently. In this section, we propose three strategies that can ease and automate the process of penalty factors tuning.

A. Reduce Number of Penalty Factors

As the best strategy to ease the process of tuning penalty factors, microgrid controller should expose less penalty factors to the user. So, it is of interest to reduce the number of penalty factors that user needs to tune.

Recall from section II.C, soft constraints associated with DER power limits, load power, and renewable power are mainly used to ensure power balance in microgrid is met. Therefore, if we can ensure that the power balance is guaranteed in the microgrid, we can avoid these constraints, thereby not introducing the relative penalty factors in the controller. To do so, a slack variable for the power balance is introduced in optimization problem which can take care of $P_i^{Violate-}[t]$, $P_i^{Violate+}[t]$, P_i^{Shed}, and $P_i^{Curtail}$ in the optimization problem. In fact, the aggregated value of the mentioned variables is presented by power balance slack variable which is defined as

$$P^{Slack}[t] = \sum_{i=1}^{N_L} P_i^{Shed}[t] - \sum_{i=1}^{N_R} P_i^{Curtail}[t] + \sum_{i=1}^{N_{DER}} P_i^{Violate+}[t] - \sum_{i=1}^{N_{DER}} P_i^{Violate-}[t], \quad (8)$$

where, $P^{Slack}[t]$ represents the power balance slack variable at time step $[t]$. $P^{Slack}[t]$ can be reflected as a penalty into the object function through

$$Penalty^{Slack}[t] = PF^{Slack}|P^{Slack}[t]|, \quad (9)$$

where at time step [t], $Penalty^{Slack}[t]$ is the penalty factor associated with the power balance slack variable and $|.|$ indicates the absolute value function. Note that $P^{Slack}[t]$ can get positive and negative value, while the penalty contributing to objective function should be always positive. The usage of $|P^{Slack}[t]|$ is to ensure $Penalty^{Slack}[t]$ is always positive.

Using $P^{Slack}[t]$ can relax the soft constraints and there is no more need for inclusion of power variables $P_i^{Violate-}[t]$, $P_i^{Violate+}[t]$, P_i^{Shed}, and $P_i^{Curtail}$ in the optimization problem. Therefore, the user just deals with PF^{Slack} instead of several penalty factors introduced by $PF_i^{Violate-}$ and $PF_i^{Violate+}$ for $i \in \mathcal{N}_{DER}$, $PF_i^{Curtail}$ for $i \in \mathcal{N}_R$, PF_i^{Shed} for $i \in \mathcal{N}_L$.

The $P^{Slack}[t]$ determines the extent to which there is excessive generation or excessive load in the microgrid. Note that $P^{Slack}[t]$ will be used then in a post-optimization process to determine which renewable resource needs to be curtailed or which load needs to be shed. In the lack of individual penalty factor for the loads and the renewable resources, the user needs to define the priority for renewable resource curtailment and load shedding. This is aligned with the desired operation where operators expect to have priorities on renewable curtailment and load-shedding. In this regard, using of $P^{Slack}[t]$ along with the list of loads and renewable resources priorities in the post-optimization process will do the job of power balance requirement.

B. Per-Unitize Penalty Factors

In the optimal dispatch problem, different costs are involved, including, time-of-use (TOU) electricity price, fuel cost of diesel and gas generators, operation cost of storages, etc. The value of penalty factors should be selected according to the mentioned prices. Therefore, every time that these prices are changed, the user needs to go through all the penalty factors and update them accordingly. This may involve extensive study to achieve coordinated and optimal value for penalty factors. In this paper, it is proposed to consider a basis for the penalty factors and per-unitize all the penalty factors according to this basis. Microgrid Controller vendor then offers a good default penalty factor values in per unit that do not need to be modified in most of the cases. Even in special cases where the default values do not properly work, a one-time tunning of per-unitized penalty factors is sufficient and with electricity price changes in future all penalty factors will be updated accordingly.

Among the prices involved in the optimal dispatch problem, TOU electricity price as well as generators price are the most changeable prices, while storage operation price is not changing frequently. TOU is a day ahead price and in the optimization horizon its values are given. Therefore, the maximum value of TOU over the optimization horizon can be calculated.

$$Price_{TOU}^{Max} = \max_{t \in \mathcal{N}_T} \{Price_{TOU}[t]\} \qquad (10)$$

Generator operation cost depends on different factors such as fuel cost as well as the efficiency and power generation of the generator. It is a fair assumption that the fuel price does not change over the optimization horizon, so the maximum operation cost of generators can be calculated as:

$$Price_{Gs}^{Max} = \max_{g \in \mathcal{N}_G} \left\{Price_{g}^{Max}\right\} \qquad (11)$$

Given the maximum price of electricity and maximum cost of generators, the maximum price related to operation of the microgrid can be calculated

$$Price_{base} = max\{Price_{TOF}^{Max},\ Price_{Gs}^{Max}\} \qquad (12)$$

$Price_{base}$ can be used as a basis for the penalty factors. By doing so, the penalty factors are always updated according to the maximum price related to the operation of a microgrid and will be tuned subsequently. Hence, a per-unit penalty factor can be defined as follows

$$PF(p.u.) = \frac{PF}{Price_{base}} \qquad (13)$$

C. Range of Penalty Factors

Through the process explained in Section III.A, the number of penalty factors was significantly reduced to three main categories, namely power balance penalty factor, i.e., PF^{Slack}, SOC violation penalty factors, i.e., PF_i^{SOC} for $i \in \mathcal{N}_S$, and smooth operation penalty factors, i.e, PF_i^{Smooth} for $i \in \mathcal{N}_S$. Also, as explained in section III.B, the remaining penalty factors are per-unitized to get updated automatically, and user does not need to retune them based on the changes in operation prices. In this section, we explain the proper default value and the proper range for these reduced and per-unitized penalty factors.

The power balance penalty factor has a significant role in the operation of microgrid. It is undesired to do the load shedding or renewable resources curtailment, while there is an opportunity to exchange power with the grid and to decrease/ increase the power of generator. In this regard, the penalty factor associated with the power balance should be always greater than the maximum operation price, i.e.,

$$PF^{Slack}(p.u.) > 1 \qquad (14)$$

By selecting $PF^{Slack}(p.u.)$ greater than one, it is guaranteed that load shedding, renewable resources curtailment, and exceeding DERs power limits do not happen when there is a chance to keep the power balance through exchanging the power with the grid or generator power contribution.

Storage SOC limit violation would happen in rare condition to make real-time operation of microgrid feasible. However, this violation should not interfere with normal operation of the microgrid. In this regard, the penalty factor of SOC violation should be always greater than the power balance penalty factor to ensure that the SOC violation does not affect the power balance requirement in the microgrid. Hence, the penalty factor associated with the SOC violation should be always greater than power balance penalty factor, i.e.,

$$PF_i^{SOC}(p.u.) > PF^{Slack}(p.u.), i \in \mathcal{N}_S. \qquad (15)$$

The purpose of storage smooth operation soft constraints is mainly for avoiding immediate changes in storage power and it does not affect the feasibility of the optimization problem solution. However, from real-time operation perspective, the smoothing of storage operation should not be at the cost of causing load shedding or renewable resources curtailment. Hence, the smooth operation penalty factor should always be less than the power balance penalty factor, i.e.,

$$PF_i^{Smooth}(p.u.) < PF^{Slack}(p.u.), i \in \mathcal{N}_S. \qquad (16)$$

IV. Case Study

In this section, the performance of the proposed strategies for turning the penalty factors in optimal dispatch problem is evaluated. To this end, ETAP software tool is utilized to model and simulate the studied system. The CPC package is utilized to solve the optimization problem.

The microgrid used in this study consists of a 1 MW wind turbine, a 1 MW PV solar unit, 1 MW diesel generator, and a total of 4 MW loads consisting of five identical loads, and one energy storage systems rated 5 MWh. The nominal voltage of the microgrid primary side is 13.2 kV and secondary side is 0.6 kV. Rest of the system parameters are provided in TABLE I. Fig. 1 shows the schematic diagram of the system.

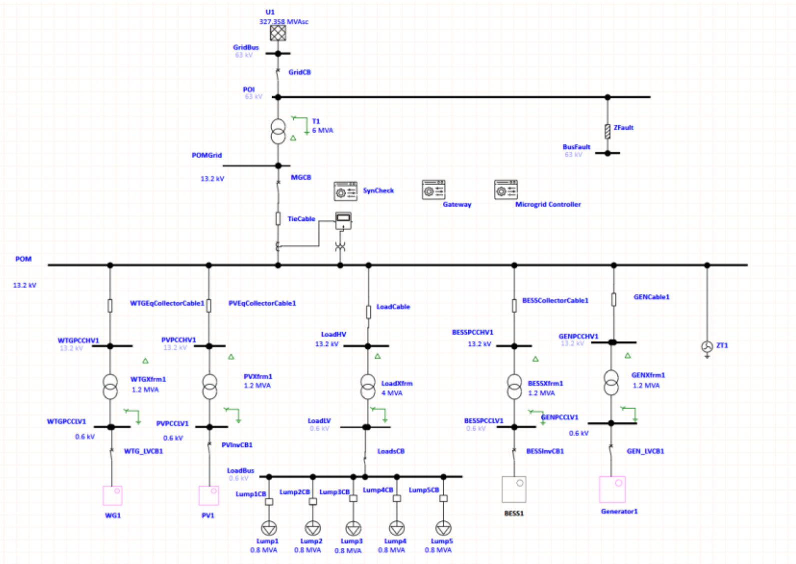

Fig. 1. Schematic diagram of the case study microgrid system

TABLE I. Parameters Used for Study Case

Parameter	Value
Maximum Export	0.0 MW
Maximum Import	1 MW
Maximum SOC	90%
Minimum SOC	10%
Initial SOC	50 %
Smooth Operation Penalty Factor	0.5 p.u.
Power Balance Penalty Factor	3 p.u.
SOC Violation Penalty Factor	5 p.u.

The results of optimal dispatch over a 24-hour time horizon are shown in Fig. 2. According to the results, BESS is scheduled to charge between 2:00 to 5:00, which helps to avoid the power exporting to the grid and between 13:00 to 16:00, which helps to increase the stored energy for the future usage. BESS also discharges between 17:00 to 22:00 when the load is large, and it is utilized for peak load shaving. Besides, the generator becomes available after 17:30 to contribute to the load compensation to keep the imported power around 1MW, which is the maximum import power limit allowed for the microgrid. The small violation of imported power between 16:00 to 18:00 is due to the fast load changing during this period. The optimal dispatch does not have a chance to regulate the power between two executions. In this regard, running faster active power control based on defined rules between two executions of optimal dispatch would help to avoid such violations, which is beyond the scope of this paper.

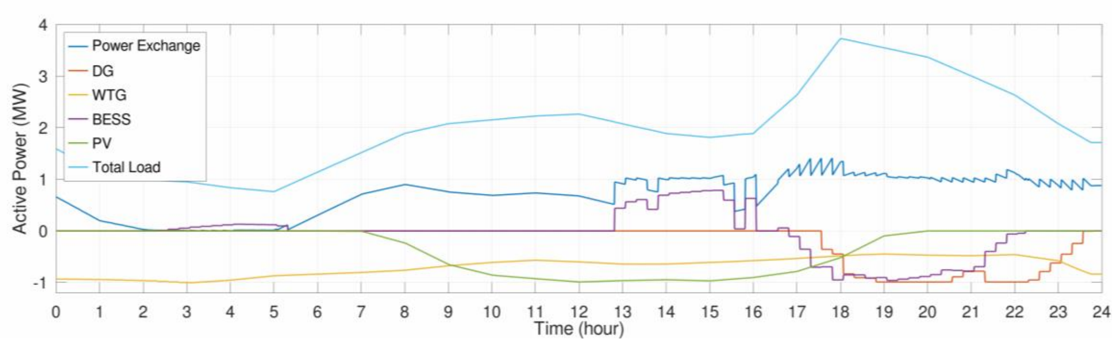

Fig. 2. Optimal dispatch results for one day.

V. CONCLUSION

Penalty factors significantly impact on effective and optimal utilization of energy resources within a microgrid. The process of tuning penalty factors needs a knowledgeable user both in optimization and power system. This paper proposed three strategies to minimize the efforts of tuning penalty factors. First, it is proposed to combine power balance variables used in optimal dispatch problem and come up with one slack variable for power balance which needs one penalty factor. Second, a base price is proposed to per-unitize the penalty factors, which facilitates the auto tuning the penalty factors upon changing the prices in the microgrid. Finally, a tailored range is defined for penalty factors, which guarantees the proper solution of optimal dispatch and avoids any mis-operation in the microgrid. The effectiveness of the proposed penalty factors is demonstrated by running the optimal dispatch problem over one day.

BIBLIOGRAPHY

[1] IEEE Standard for the Specification of Microgrid Controllers. (IEEE Std 2030.7-2017, pp.1-43, 23 April 2018)

[2] M. R. D. Zadeh et al., “Design and implementation of a microgrid controller”. (64th Annual Conference for Protective Relay Engineers, College Station, TX, 2011)

[3] M. R. Dadash Zadeh, A. Mazloomzadeh, H. Ghaffarzadeh and H. Castro, “Model-Driven Microgrid Controller”. (FISE-IEEE CIGRE Conference - Living the energy Transition, Medellin, Colombia 2019)

[4] A. G. Tsikalakis and N. D. Hatziargyriou, “Centralized control for optimizing microgrid operation”. (IEEE Power Energy Socity General Meeting, San Diego, CA, USA, 2011)

[5] N. Hatziargyriou et al., “Energy management and control of island power systems with increased penetration from renewable sources”. (IEEE Power Energy Society Winter Meeting, New York, NY, 2002)

[6] H. Hajimiragha et al., “Microgrids Frequency Control Considerations Within the Framework of the Optimal Generation Scheduling Problem”. (IEEE Transaction on Smart Grid, vol. 6, no. 2, pp. 534-547, March 2015)

[7] A. Hajimiragha and M. R. D. Zadeh, “Practical aspects of storage modeling in the framework of microgrid real-time optimal control”. (IET Conference on Renewable Power Generation, Edinburgh, 2012)