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Power Scheduling and Control Schemes for Efficient Operation of a Solar Power in Hybrid DC Microgrids

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ABSTRACT

In this paper, a hybrid DC microgrid consisting of a diesel generator with a rectifier, a solar photovoltaic (PV) system and a battery energy storage system is presented in relation to an effective power management strategy and two different control techniques implemented for power electronic interfaces. The solar PV and battery energy storage system are considered as the main source of energy that supply the load demand on a regular basis whereas the diesel generator is used as a backup for the emergency situations. All system components are connected to a common DC bus through an appropriate power electronics devices (e.g. rectifier systems, DC/DC converter). Also a detailed sizing philosophy of all components along with the power management strategy is proposed. Monthly basis energy distribution patterns of each individual component have also been presented. The power delivered by the solar PV system and diesel generator is controlled via DC-DC converter and excitation controller which are designed based on a linear quadratic regulator (LQR) technique as well as proportional integral (PI) controllers. The component level power distribution is investigated using these controllers under fluctuating load and solar irradiation conditions and comparative results are presented.

Keywords:— *DC microgrid, solar PV system, diesel generator, battery energy storage system, sizing of components, energy management.*

I. INTRODUCTION

DC microgrids are used to satisfy the load demand of remote locations such as telecommunication and railway sites. Such microgrids generally consist of a diesel generator, a battery energy storage system, and a renewable energy source to perform the hybrid operation. In most of the cases, solar photovoltaic (PV) systems are considered as the preferred source of renewable energy for a DC microgrid due to several advantages such as less capital cost, environmental conditions (i.e., open areas leading to high sun density) and low complexities associated with the structural requirements. Most of the remote locations are very difficult to reach and thus, the continuous fuel (e.g. diesel, coal, gas) supply is not possible. The operation of diesel generators mainly depends on the availability of fuel and therefore, its role is limited as a backup/emergency supply [1]. The battery energy storage system (BESS) is considered as one of the most reliable sources of energy as it can be charged either via a solar scheme or a diesel generator. However, the size of the battery storage system plays a significant role in determining the overall capital cost of a DC microgrid system as well as the autonomy of operation. Therefore, the selection of the battery storage capacity should be made with a view to achieve an optimized cost while maintaining the supply reliability [2]-[4].

Industry standard DC power systems can be designed to supply the loads with 12 V, 24 V, 48 V, 110 V or even higher. If the load requires different output voltage levels, suitable DC/DC conversion schemes can be employed to achieve the appropriate voltage levels. However, such a DC/DC conversion can lead to a single point of failure. There are several factors which should be considered when designing a microgrid systems. One of the most important critical design inputs is the load analysis of the remote site, autonomy time for the battery storage, the size of the diesel fuel tank, shading effects and wind loading factors for solar, etc. [5]-[7]. Most of the above stated information can be directly obtained by having a site visit or through a consultation with the owner of the project. There are several power electronic interfaces involved with the operation of DC microgrids. All major energy sources (i.e. solar PV, diesel generator and battery storage systems) are connected to a common DC bus through rectifiers and/or regulators. In this regard, redundancies of the components (e.g., N+l) and their reliability of operation are para important. Also, proper electrical protection schemes (e.g., over voltage, transient over voltage, low voltage battery disconnection, etc.) should be incorporated to the microgrid considering many design aspects such as coordinated discrimination [8].

The power management of DC microgrids is another important challenge as the overall operational efficiency depends on the power sharing capability of the system components [9]. As far as the stability is concerned, the regulation of the DC bus voltage is a key challenge [10]-[12]. The DC bus voltage is regulated based on the power balance of the microgrid system. However, the control of power balance is a challenging task as it involves with detailed control design for the power electronic interfaces [13]- [15].

This paper aims to provide a detailed analysis of a commercial hybrid DC microgrid which can be widely adopted by telecommunication and railway industries. An analytical framework is proposed for sizing different components of DC microgrids. Moreover, the excitation system and rectifiers of the diesel generator along with DC-DC converter are controlled by employing linear quadratic regulator (LQR) controller. In this regard, different operational modes of the DC microgrid are considered: over generation, under generation and emergency cases. Also, the performance of the proposed controller is evaluated against a traditional proportional integral (PI) controller. Simulation studies are carried out to justify the analytical framework for sizing and power management with the proposed controllers under different operating conditions.

The paper is organized as follows. Section II includes the overview of a commercial DC microgrid. Section III is presenting the analytical framework for sizing different components such as loads, solar PV systems, BESSs, and diesel generators. Section IV represents the hybrid operation of the DC microgrids and section V presents the controller design techniques while Section VI provides the relevant simulation results. Finally, Section VII summarizes the main outcomes and scopes for the future works.

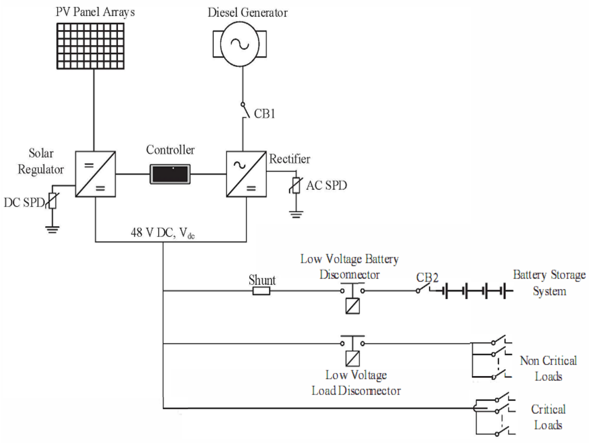

Figure 1: A Commercial Hybrid DC Microgrid System.

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II. STRUCTURE OF A COMMERCIAL DC MICROGRID

In this paper, a commercial hybrid DC microgrid that can be employed for telecom and railway power applications is considered. The microgrid is consisting of the following main components:

1. A diesel generator with a rectifier,
2. A solar PV system with a DC-DC converter (solar regulator),
3. A BESS which directly connected to the DC bus, and
4. DC loads (critical and noncritical)

The proposed hybrid DC microgrid is shown in Figure 1. It can be seen that all components (except DC loads or the BESS) are connected to the DC bus either via DC-DC converters (e.g. solar PV system via a solar regulator) or via the rectifier (e.g. diesel generator)

The DC loads can be connected directly to the system output if the rated voltage of the loads is similar to that of the DC bus. However, a AC –DC uck or boost converter is required to connect the DC loads if a different voltage is required than the DC bus voltage, Vdc. The component sizing and practical design are considered as the key elements of the design process of a DC microgrid and they are discussed in the following section.

III. SIZING AND PRACTICAL DESIGN CONSIDERATIONS

This section is intended to illustrate the components sizing associated with the DC microgrid depicted in Figure 1. There are many factors which influence the sizing of different components in a microgrid. Among these factors, the overall costs (capital and operating) and supply reliability are considered as dominant elements. Some designs may be cost competitive while trade- off other important features such as the autonomy time (i.e. the continuity of the power supply). The sizing of different components in a commercial hybrid DC microgrid is illustrated below:

A. Sizing of Loads

DC load demands are generally provided by the project developer. The DC load is mainly consisting of the customer load ($P_{L\ Site}$) which is used to supply the site equipment (e.g. signaling device). However, additional DC power ($P_{L\ Cubical}$) that required to operate the controllers of micrgrids should be taken into consideration. For example, most of the batteries used in microgrid environments are placed in IP5X or IP6X rated cubicles that consist of cooling system (e.g., fan, heat exchanger or DC air conditioner, control units power supply). Therefore, the DC power consumption associated with the cooling system should be considered. In some situations, the extra power requirement (i.e $P_{L\ Cubical}$) can be greater than the actual site load ($P_{L\ Site}$). Therefore, the total load of the site can be calculated as in equation (1).

$$P_{L\ Total} = P_{L\ Cubical} + P_{L\ Site} \quad \text{..................} \quad (1)$$

where P_{Load} is the total power for the designed microgrid, PL_{site} is the power consumed by the site loads, and is the additional load requirement due to the presence of cubicles (cooling, charger control supply, etc.).

B. Sizing of BESS

The BESS can be considered as the most critical component of the proposed DC microgrid. The autonomy or continuous running time of the microgrid system mainly depends on the capacity of the BESS. In general, the autonomy time of the battery storage system for a microgrid can be 3 to 7 days. However, longer running time means the higher cost and therefore, the size of the BESS should be estimated without compromising its supply quality. The depth of discharge (DOD) is one of the key parameters for sizing the BESS. If the battery is charged to 100% of its capacity defined by %C battery and the autonomy time is t autonomy (e.g. 7 days), where DOD battery is the DOD for the battery, %C battery is the percentage capacity of the battery, and $t_{\ autonomy}$ is the time to maintain the continuity of the supply through the battery. The DOD for the battery (DOD battery) decreases with the increase in the time for the autonomy (t autonomy) which is illustrated in Figure 2.

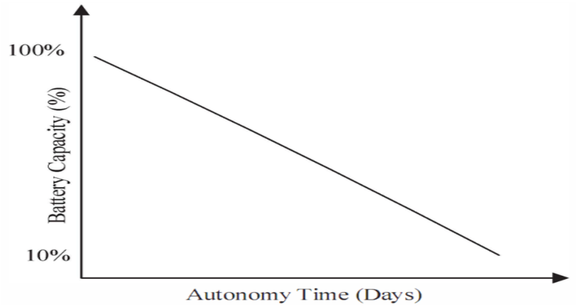


Figure 2. Battery capacity over autonomy time (It is assumed that battery is being discharged following linear characteristics)

The ampere-hour (Ah) capacity of the battery can easily be calculated if the following items are known:

- load voltage,
- total power of the load
- time for autonomy, the DOD,
- aging factor (AF), and
- temperature compensation factor (TC)

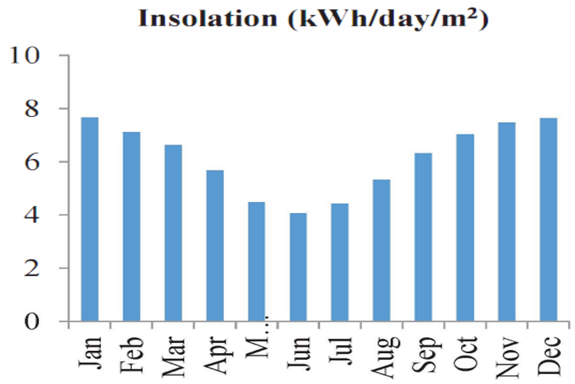


Figure 3. Insolation level of the site location

C. *Sizing of Solar PV System*

The size of the required solar panels depends on many factors such as shading, albedo setting, etc. However, a detailed analysis of these factors has not been included in this paper. The sizing of the panels is mainly determined by considering the insolation levels of each month where the insolation level for a year is shown in Figure 3 and the designed total load (PL,o,ªJ of the site. The effective area of the solar panel is a measure of area that solar panels should have under the standard operating condition

Prated(Panel) is the solar panel rating in Watts, irradiance at standard conditions, and 1](Panel) is the efficiency of the solar panel.

The number of panels, NPanels required based on the lowest irradiance level on a monthly basis (In this case, the lowest irradiance level is in June as shown in Figure 3)

D. Sizing of Diesel Generator

In this paper, the sizing of the diesel generator is estimated by considering two parameters:

1. (a) total designed load (PL, o, a') and
2. (b) Charging rate of the battery (typically Cs or ClO).

Different components of the DC microgrid as shown in Figure 1 are determined based on these sizing approaches and the hybrid operations are discussed in the following section.

III. HYBRID OPERATION OF DC MICROGRIDS

The operating modes of the hybrid DC microgrids depends on the load demand, available capacity of the BESS, power output from the solar PV system and power supplied by the diesel generator. There are several uncertainties associated with the operational performance of the microgrid system:

(a) varying load and

(b) fluctuating weather conditions.

Therefore, controllers are required to regulate the output power of all components with a view to maintain the power balance. In this regard, the DC bus voltage, Vdc is taken as the desired control objective. The power balance equation of the hybrid DC microgrid system depicted in Figure 1 can be written as in equation (7):

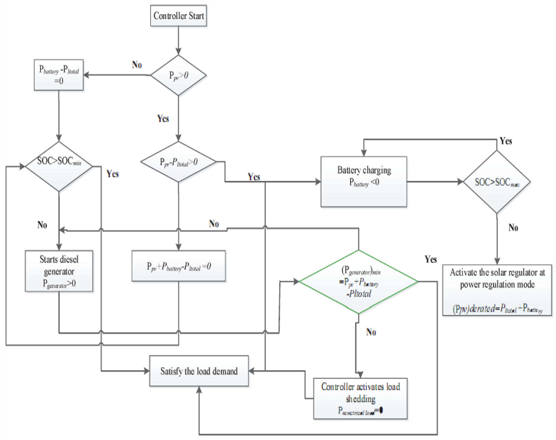


Figure 4: Power Management Scheme

where $V_{regulator}$ is the operating voltage of the regulator is the operating power of the regulator, and the subscripts "min" and "max" correspond the minimum and maximum values of the respective variables. The role of the BESS in a hybrid DC microgrid is to supply the load when the solar PV systems do not generate sufficient power to match the load demand. It is to be noted that the availability of the battery storage system is subjected to following condition:

SOCmin < SOC :s; SOCmax

where SOC is the state of charge of the battery, SOCmin (e.g. 40%) is the minimum limit of the SOC and SOCmax (e.g. 90%) is the maximum limit of the SOc. The diesel generator is controlled to supply power when there is no power from the solar PV system as well as the energy stored into the BESS is not sufficient to deliver the loads. The output power of the diesel generator is usually controlled through the governor-excitation system. A rectifier system (ACIDC conversion) should be incorporated to interface the diesel generator with the DC bus. However, the power output of the diesel generator should meet the minimum power requirement min to avoid operating at lower efficiency. In general, the minimum loading of the diesel generator should be 30% of its rated power output. If this condition is not met, the load shedding scheme should be employed. Non-critical loads C where Ppv is the output power of the solar PV system, and Pbattery is the power available from the battery. The '±' sign is used for Pbattery as the battery can supply or store energy, i.e., it allows discharging and charging, respectively. The output power of the solar PV system is fluctuating and therefore, a solar regulator is used to supply the power into the DC bus where the loads are connected. In the DC microgrid, the power available from the solar PV system is utilized either by supplying the load or by storing excessive energy into the BESS. Therefore, it is essential to control the solar regulator in a manner that it does not operate outside the specified limits of DC bus voltage. For example, the solar regulator should have specified input voltage and power limits that need to be taken into consideration. The power limits of a solar also determine the number of panels that can be connected to a regulator. These voltage and power limits can be written as followsan be connected via low voltage load dis-connector as shown in Fig. 1. The control operation of each component is based on the power management scheme as depicted in figure 4.

In this paper, the controllers for the converter of the solar PV system and the excitation system of the diesel generator are designed by using a linear quadratic regulator (LQR) approach as discussed in the following section.

IV. CONTROLLER DESIGN

The controllers are designed based on the dynamic model of the diesel generator and solar PV system. The diesel generator is mainly a synchronous generator and its excitation system can be controlled to maintain the terminal voltage within the rated value. Similarly, the output power of the solar PV system can be controlled via the DC-DC converter. The dynamical models of the diesel generator and solar PV system along with the controller design technique are discussed in following subsections:

A. Dynamical Models of the Diesel Generator and Solar PV System

As stated above, the diesel generator is a synchronous generator and its dynamical model is used to design the excitation controller. A synchronous generator can be represented in different ways based on its intended applications. In this paper, the one -axis model of the synchronous generator is used along with the dynamics of the excitation system. The one-axis model of a synchronous generator along with the mechanical dynamics can be written as follows [16]:

$$\begin{aligned}\dot{\delta} &= \omega - \omega_0\\ \dot{\omega} &= -\frac{D}{2H}(\omega - \omega_0) + \frac{\omega_0}{2H}(P_m - P_e)\\ \dot{E}'_q &= -\frac{1}{T'_{do}}E'_q - \frac{(x_d - x'_d)}{T'_{do}}I_d + \frac{1}{T'_{do}}E_{fd}\end{aligned}$$

where <5 is the rotor angle, w is the operating speed, Wo is the synchronous speed, D is the damping coefficient, H is the inertia constant, Pm is the mechanical power input, Pe is the electrical power output of the synchronous generator, E q^1 is the field variable proportional to field flux linkages, T ^{1}do is the d-axis transient open-circuit time constant, Xd is the d-axis synchronous reactance,

V. RESULTS

The performance of the proposed commercial hybrid DC microgrid shown in Figure 1 is investigated by considering two main aspects:

1. The sizing philosophy as discussed in Section III and on the basis of monthly energy distribution and
2. The operational strategy as discussed in Section IV. The corresponding results are presented in the following two subsections:

A. Validation of Sizing Philosophy

As mentioned earlier, the micro grid system comprises of a diesel generator, a solar PV system, a BESS, and loads. The sizing of these components are carried out by considering the formulas as presented in Section III and listed in Table I. Different operational conditions are considered. In this regard, the operation of the DC microgrid with different solar panel sizing, diesel generator and battery storage have been presented. Following assumptions have been made when analyzing the monthly energy distribution:

1. Solar irradiation is constant throughout the month and the effective solar period is 4 hours per day
2. Battery is supplying energy to the load during the rest of the day

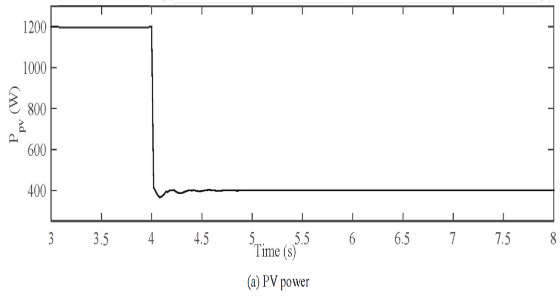
If battery capacity drops to 50% of its DOD, the diesel generator is kicked in and supplying the load and charging the battery at ClD rate

All simulations are conducted based on the remote location which is having insolation levels as depicted in figure 3. Three cases have been chosen based on the selection of different numbers of solar panels. In the first case, the number of solar panels is selected as 24 which represents an ideal case for the microgrid as shown in Fig. 8. There are no energy wastage and maintain the consumption of diesel energy and battery discharge energy at moderate levels. It can be noticed that the highest battery charging energy is exhibited during the month that corresponds to the highest solar energy generation. Also, the battery discharging and diesel energy have been increased during the low solar irradiation months such as in July.

In the second case, 60 solar panels are selected which rep- resents an oversized scenario and the energy profile. As anticipated, the energy wastage occurs due to the excessive power generation from the solar panels. As stated above, under practical situations such excessive or wasted energy will be controlled via the solar regulator. Also, it can also be seen that there is an increase in battery charging energy due to the availability of high power generation from the solar panels resulting a reduced energy contribution from the diesel generator.

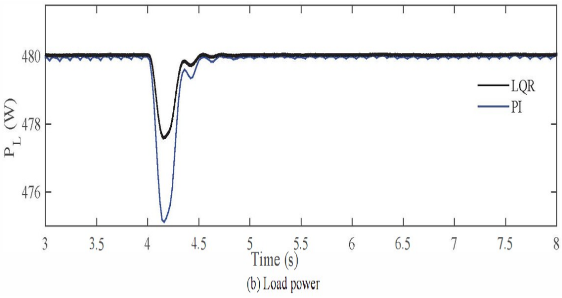
The third case represents an undersized solar requirement and the energy distribution is shown in Figure 10. It can be noted that, the battery charging energy has been reduced as compared to previous two cases. Also, the energy component corresponds to the battery discharging is increased due to the reduced solar generation. Similarly, the diesel generation has been increased significantly compared to the first two cases.

Figure 11 shows the DOD of the battery with the estimated capacity. In this paper, the autonomy time for the battery is taken as 3 days which corresponds to 30% DOD/ day. Also it is evident from Figure 11 that the lower DOD increases with the size of the battery storage system. The operational strategy of the DC microgrid is discussed in the following subsection.



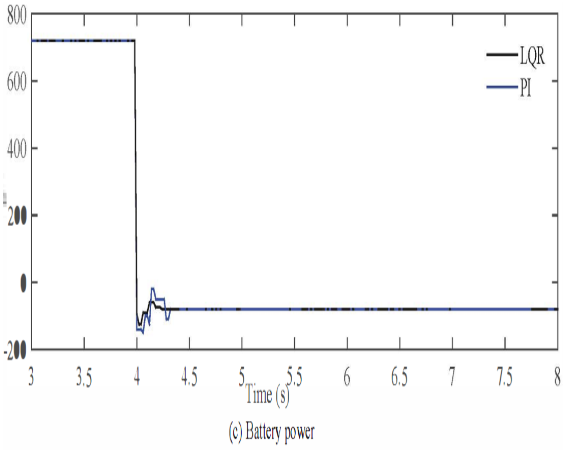
(a) PV power

Figure 5: Photo voltaic Out power



(b) Load power

Figure 6: Power available across the Load



(c) Battery power

Figure 7: Battery power

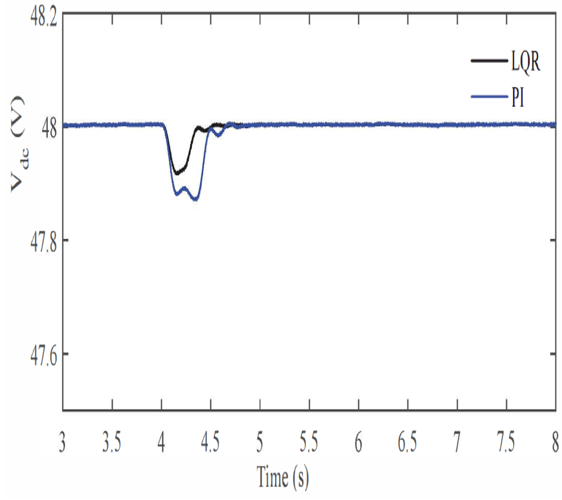


Figure : Dc Link Voltage With LQR and PI

VI. CONCLUSION

In this paper, a solar PV dominated hybrid DC microgrid has been explored whose applications are mainly considered for telecommunication and rail industries. The investigation is conducted by considering all basic components of an industrial or commercial DC microgrid while emphasizing the importance of the proper sizing as well as power management scheme and different control strategies. Monthly energy distribution is presented along with system level performance under variable load and solar conditions. From the analysis, it has been identified that the appropriate sizing of microgrid components is important for the efficient operations as there will be excess energy due to over sizing while there will be lack of energy due to the under sizing of these components which have been justified using simulation studies. Moreover, the appropriate sizing of the components also ensures a stable dynamic operation of DC microgrids which have been justified through the design of LQR controllers and dynamic simulations under different operating scenarios. Comparative results are presented to demonstrate the performance of LQR controllers over the traditional PI controllers and these results indicate the superiority of the LQR controllers. Future work will deal with the incorporation of an AC microgrid to supply the local communities in the remote area along with telecommunication and rail industries.

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