Load Control between PV Power Plants and Diesel Generators

Mohamed Khalil Abdalla MohamedAli, AISHA HASSAN ABDALLA HASHIM, OTHMAN KHALIFA

International Islamic University Malaysia
KULLYIAH OF ENGINEERING

Abstract
Introducing renewable energy sources, such as wind and photovoltaic arrays, in microgrids that supply remote regions with electricity represents a significant leap in electricity generation. Combining photovoltaic panels and diesel engines is one of the most common ways to supply electricity to rural communities. Such hybrid systems can reduce the cost of electricity generation in these remote power systems because they use free energy to balance the power generated by diesel engines. However, the combination of renewable energy sources and diesel engines tends to complicate the sizing and control of the entire system due to the intermittent nature of renewable energy sources. This study sought to investigate this issue in depth. It proposes a robust hybrid controller that can be used to facilitate optimum power sharing between a PV power source and diesel generators based on the dynamics of the available PV energy at any given time. The study also describes a hybrid PV-diesel power plant's essential functional parts that produce electricity for a microgrid using a renewable energy source. Power control needs to be adjusted to reduce the cost of power generation.
Keywords:
Load Control, PV Power Plants, Diesel Generators.

1. Introduction

In recent decades, hybrid grid systems, which combine fossil fuels and renewable energy sources, have become increasingly popular. This is especially true now that the cost of fossil fuels has significantly increased while the cost of photovoltaic (PV) power systems has decreased. Combining renewable energy resources and diesel gensets has become one of the most common approaches to generating electricity for isolated communities. This is because electricity supply through the extension of transmission lines from the national power grid to such communities can be expensive and even impossible due to geographical barriers. For this reason, such communities have to use their own electrical power generation distribution systems to meet their own power needs. Such schemes are known as micro-grid systems [1].

Typical diesel generators, utility networks, and storage systems are combined in micro-grid systems with renewable energy sources like solar and wind power.. They are characterized by limited power levels, isolation from the national power grid, and a low-voltage distribution system. Their primary power source usually consists of a hybrid PV-Diesel power generator. Diesel gensets combine a diesel engine with an alternator to produce electricity. The other ancillary gadgets include a base, sound attenuation, a canopy, good control, a starting system, jacket water heaters, circuit breakers, and control systems. Most diesel compression-ignition engines are designed to run on diesel, albeit some are adapted to natural gas or other fuels. Diesel gen-sets are usually the only power sources in microgrids in remote areas in developing countries. Still, currently, they are used for more complex applications, including peak-lopping, export to the power grid, or grid support [2].

The key issue about diesel gensets is the fuel cost, including the cost of transporting the fuel. Zanarini and Ragazzini note that transporting one liter of diesel to some remote rural locations may cost as much as one liter of gas, which is considerably high [3]. In this regard, integrating diesel gensets with a RES, like a photovoltaic (PV) power plant, greatly reduces fuel consumption and the cost of generating electricity and genset pollution. Thus, the primary advantages of hybrid mini-grid systems are that they reduce fuel consumption and ensure a steady supply of power.

Solar PV power generation is the most commonly used renewable energy source in microgrids and distributed generation. PV power stations consist of an array of photovoltaic nodules that directly convert light energy into electricity, which is then supplied as merchant power into an electrical grid. Most PV power plants are developed with a minimum power production scale of 1 MW_p (megawatt-peak), i.e., the DC power output of the solar array. As of 2017, the world's largest running PV power plant produced more than 1500 megawatts of electricity, albeit projects for up to two gigawatts were underway [4]. Diesel gensets are integrated with PV power plants to guarantee a continuous supply of power when solar energy is unavailable.

The motivation for this study is the increasing urgency to reduce the carbon footprint of fossil fuels power plants by allowing diesel engines (DGs) in micro-grids to continuously operate with minimum load. Much of the global population still largely depends on fossil fuels power plants, including coal and natural gas and oil power plant, for their electricity, notwithstanding the threat of global warming and the fact that sustainable energy sources have had significant penetration into the energy industry. Ganesan, Ramesh, and Umashankar [5] also explain that the energy demand is rising sharply because of the increase in the world's per capita energy consumption, which is

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causing a rapid depletion of conventional energy sources reserves. The initiatives to integrate sustainable energy sources into the regular energy networks are especially motivated by new government-sponsored drives, such as feed-in tariffs and the introduction of federal tax incentives. With the cost of diesel at over $1 per liter and diesel engines (DGs) running continuously, PV sources can significantly reduce diesel consumption by allowing DGs to continuously operate with minimum load. In addition to lowering diesel usage, a hybrid controller will keep the DG's spinning reserve at a constant level to prevent power outages. This would be the ideal choice for installations where the PV penetration is 20–60% and diesel costs are higher than $1. In light of this, the following equation can be used to limit PV generation:

PV_{max} = Total Load – DG_{min}; [5].

2. Significance

Grid-tied PV power generators connected to the power system network would stop operating if the utility grid failed, i.e., went into an off-grid mode, because solar power cannot function as a "stand-alone" source of energy. The DGs will turn on and start delivering loads. In essence, because they are not made to serve in this way, grid-tied PV generators cannot work alongside DGs in an off-grid mode to share loads. Due to the need to carry the entire load until the power grid is restored, this condition increases fuel consumption and energy costs. Hybrid controllers must be used for the grid-tied PV generators and the DGs to operate together in an off-grid mode. The hybrid controller can be designed to manage the power flow and control the micro-grid to allow smooth load dispatch and reliable operation. The controller will ensure the DGs always function above the minimum required generator load to maintain the minimum DG power losses during conversion. Also, it will curtail the PV generator output to protect the DGs from reverse power feedback.

Moreover, the controller can be configured with specially formulated control algorithms to perform the hybrid control functions in such a way that they minimize the maintenance costs and guarantee the longevity of the DGs. This research proposes to investigate the effectiveness of a hybrid control scheme in facilitating optimum power sharing between a PV power source and DGs based on the dynamics of the available PV energy at any one time. The alternations in generation are primarily the result of the intermittency of the PV source, as well as the amount of energy stored in batteries. The control of power flow in the hybrid system is thus achieved by regulating the active power produced by the PV inverter and the DGs as a function of the system frequency notably in the islanded mode of the micro-grid operation.

The absence of the main grid and relay information to both the PV generators and DGs to synchronize the two sources and ensure that the micro-grid works reliably by giving the right reference voltage and frequency measures over the whole network. This researcher proposes a robust hybrid controller and regulating plan for the aforementioned functionality.

3. Literature Review

According to the World Bank’s Global Tracking Framework, 1.06 billion persons have no access to electricity, and most of such people (80%) live in the rural areas of Asia and Africa [6]. While rapid progress has been made toward rural electrification over the last two decades, there is still much ground to cover to finish the work. Access to electricity is critical for social development, public health, and local economic development. In this sense, the absolute priority for technically all governments and global organizations is 100% global electrification. Supplying electricity to remote areas, however, is far from being reckoned an accessible business due to the costs involved. Two alternatives are normally considered in this effort, i.e., connecting to an existing grid or designing a local microgrid. Micro-grids are usually preferred for remote locations where building a connection to an existing grid would involve a lot of complications and high costs. Most remote communities use micro-grids for electricity supply. These grids are usually powered by one or more diesel gensets, but the increased life cycling cost of diesel generators coupled with the decreasing costs of solar array are leading most developing countries to turn to stand alone Alternative Energies or Hybrid Energy Systems (HES) [7].

4. Hybrid Micro-Grids

A Hybrid Energy System (HES) is a system that integrates renewable energy sources (RES) with other sources, such as a storage system or diesel generators to supply electricity to a load [8]. The critical advantage of hybrid systems is that they generally improve the reliability of renewable energy sources while limiting carbon emissions and the overall cost of energy production. Moreover, the storage system can be slightly reduced due to the decreased dependence on one system. The right selection of the components of a hybrid approach, its optimal sizing, and functional control are crucial but challenging steps in the lifetime of remote hybrid energy systems [9]. Optimal hybrid system’s design and functionality are usually nonlinear because of the non-linearity of features of its components, the non-linearity of the load, and the complexity of the problem. Jansen, Roos, and Terlaky [10] point out that the complexity in the resolution of optimal operation control problem lies in the dimension of the problem.

Most practical hybrid system designs and implementations, according to Seeling-Hochmuth [11], often employ conventional methods such as the "Paper-based methods" and the "Rule of thumbs approach." These strategies are based on progressive trials and experience including errors. However, they have limitations because they can only offer broad intuitive guidelines that may still be open to improvement.

So far, much research has been done using numerical methods for the sizing of hybrid system components and cost optimization based on the load demand and the available energy resources from the sites [12]. These methodologies tend to be time-consuming, and their degree of complexity rises exponentially with the number of variables or energy sources considered in the architecture of hybrid systems. What is more, is that these methods can achieve only the sizing or optimization of the initial cost of investment, but not the running cost with the mean of optimal operation control. The other mathematical approaches, including 'probabilistic techniques [12], 'Iterative methods' [13], and 'Graphic methods' [14] are based on derivatives and have proven their efficacy in handling several forms of optimization issues, albeit they cannot be used for some advanced optimization problems like operation control and combined optimal sizing.

Several other approaches, including linear programming, dynamic programming, non-linear programming, network flows, etc., are available for the resolution of optimization issues. Although these techniques involve pure mathematical analyses, they are not suited to resolve issues with high nonlinearity and are often susceptible to the problem of dimensionality. Further, various software packages for sizing and optimizing specific "predesigned" hybrid systems are also available. Such software is founded on a mathematical description of the system's energy resources and the components operational features [15, 16]. The software tools may employ a complex or linear and simplified models but randomly vary the design within a preset interval on the sizes of components. It is also essential to note that Computational or Artificial Intelligence has been proposed as an alternative to the conventional analytical approaches because of the high non-linearity and high complexity of operation control and optimal sizing.

The other modern optimization techniques include genetic algorithms, Ant colony optimization, Neural-Network, Fuzzy optimization, Particle swarm optimization, and Simulated annealing, among others. Identifying the best of these current optimization techniques calls for a detailed and accurate model that outlines the performance of the non-linear hybrid system, as well as the complex relationship between operation control and optimal sizing [17].

5. The Components of a Hybrid Energy System

The hybrid system proposed for this study consists of a diesel generator, a PV system, an inverter, a charge controller, AC and DC loads, and a battery storage system. Diesel generators, to begin with, usually constitute a diesel engine connected to an alternator to produce electricity. They can produce electricity at nominal power, and any surplus energy may be used for charging a battery bank. They are designed such that they run between 80% and 100% of the kW rating when linked together with other renewable energy systems or the battery bank. The energy a DG with a rated power output (P_{DG}) generates is expressed as:

$$E_{DG} = P_{DG} \times \eta_{DG} \times t$$

Where: η_{DG} is the DG's efficiency [18].
PV systems comprise an array of solar panels that harness the sunlight that irradiates their surfaces. Insolation or irradiance is measured in watts per square meter (W/m^2), and the output energy of the PV system (E_{PV}) can be expressed as;

$$E_{PV} = A \times \eta_m \times P_f \times \eta_{PC} \times I$$

Where: A is the entire area of the PV generator in m^2,
η_m is the efficiency of the module,
I am the hourly radiance in kWh/m^2, and
P_f is the packing factor [19].

Solar farms are in widespread use today due to the trend to minimize the use of fossil fuels, including coal and gas, and also because the production cost of PV arrays have been falling. At the same time, their efficiency and durability have had continual improvement. In this regard, PV arrays play a significant role in power generation from renewable sources. PV power supply nonetheless harbors risks and presents grid operators and energy suppliers with new challenges primarily because of its unpredictability. Also, PV panels produce no electricity at night when the sun is not shining. For this reason, issues always arise in the planning of the availability of solar energy.

Regarding the battery storage system, the battery states are at any one time linked to the last state of charge and the energy situation of the system, i.e., the produced and consumed system energy from the time ($t - 1$) to t. During charging when the total output of DG and PV panels exceeds the load demand, the present bank capacity at the t^{th} hour ($E_{Bat(t)}$) can be expressed as:

$$E_{Bat(t)} = E_{Bat,(t-1)} \times (1 - \sigma) + \left[\sum relativeparent\ IE\mathrm{i}(t) - \left(\frac{E\mathrm{AC,,load}(t)}{\eta \mathrm{Inv}} + E\mathrm{DC, load(t)}\right)\right] \times \eta_{Bat,Ch},$$

When the load energy needs exceed the power generated, additional power can be harnessed from the battery bank. The available capacity of the battery bank during the discharge process can be expressed as:

$$E_{Bat(t)} = E_{Bat,(t-1)} \times (1-\sigma) - [-\sum Ei(t) + (\frac{EAC,,load(t)}{\eta Inv} + EDC, load(t))] \times \eta_{Bat,Disch},$$

Where; $E_{Bat(t)}$ and $E_{Bat,(t-1)}$ are the available capacities of the battery banks (Wh) at t and $t-1$,

$\eta_{Bat,Ch}$ is the efficiency of the battery during charging,

$\eta_{Bat,Disch}$ is the efficiency of the battery during discharging,

η_{Inv} is the efficiency of the inverter

σ is the rate at which the battery bank self-discharges

$E_{i(t)}$ are the energies produced by the battery charger and PV panels, and

$E_{AC,load(t)}$ is the AC load demand at the t^{th} hour [19].

6. Design Variables

PV panels in series do not constitute a design variable because the overall charge is determined by the DC bus's nominal voltage, which is a constant. On the contrary, for PV panels in parallel, X_{PV} constitutes a design variable. A change in X_{PV} changes the corresponding output current of the PV array. The total output current of the PV system is dependent on variables, such as the size and type of panels that are used. It can be expressed as:

$$I_{PV,System} = I_{PV,panel} \times X_{PV}$$

Where; $I_{PV,System}$ is the entire PV system output current,

$I_{PV,panel}$ is the current output of a single PV panel, and

X_{PV} is the number of PV panels in parallel [19].

The output voltage of the AC Diesel Generator normally equals the AC bus voltage. In this regard, DGs are usually not connected in series. They can be linked in parallel to match the current requirements of the system. The immediate current output from a DG depends on variables, such as the size or type of the DG used. The operation decision variable is expressed as:

$$I_{DG} = I_{DG,max} \times X_{DG\%}$$

Where, I_{DG} is the DG's output current which is a percentage/ratio of the maximum DG current,

$I_{DG,max}$ is the maximum nominal DG current output, and

$X_{DG\%}$ is the DG output decision variable ranging from 0 to 1, in which case 1 is maximum DG output and 0 is no output [18].

The maximum direct current from the system of batteries is dependent on the state of battery charge at that instance and the maximum allowable discharging or charging rate. The instantaneous current output from a battery is a functional decision variable. It is a percentage of the maximum battery current available at that instance and can be expressed as:

$$I_{Bat(t)} = I_{Bat,max,(t)} \times X_{Bat\%(t)}$$

Where, $I_{Bat(t)}$ is the immediate current output, which is a percentage of the maximum battery current at time t,

$I_{Bat,max,(t)}$ is the maximum battery current at time t, and

$X_{Bat\%(t)}$ is the decision variable of the battery output ranging from 0 to 1 as in the case of the DG [19].

The nominal voltage of the DC bus determines the number of batteries in series which is a constant. The instantaneous current output from the entire battery bank depends on variables, such as the size or type of battery used and the number of battery strings in parallel.

$$I_{Bat(t)} = I_{Bat,max,(t)} \times X_{Bat\%(t)} \times X_{Bat},$$

The inverter size X_{Inv} can be expressed in terms of its AC power output;

$$P_{Inv\text{-}Out} = P_{Inv\text{-}In} \times \eta_{Inv} = X_{Inv};$$

In this sense, the current output can be expressed as:

$$I_{Inv\text{-}Out} = I_{Inv\text{-}In} \times \eta_{Inv} \times \frac{VDC,BUS}{VAC,BUS}$$

If the proportion of current from the DC bus redirected to the DC load is $X_{R,DC}$, the inverter input current can be expressed as (1 - $X_{R,DC}$). $X_{R,DC}$ in this sense is a working variable.

$$I_{Inv\text{-}Out} = I_{DC,Bus} \times (1 - X_{R,DC}) \times \eta_{Inv} \times \frac{VDC,BUS}{VAC,BUS}$$

Regarding the battery charger, its size X_{BC} can be expressed in terms of the DC power output;

$$P_{BC\text{-}Out} = P_{BC\text{-}In} \times \eta_{BC} = X_{BC}$$

In this sense, the input current will be expressed as;

$$I_{BC\text{-}In} = \frac{IBC-Out \times VDC,BUS}{\eta BC \times VAC,BUS}$$

The proportion of current from the DG redirected to the battery ($X_{R,AC}$) *is* an operational variable

$$I_{DG} \times X_{R,AC} = \frac{IBC-Out \times VDC,BUS}{\eta BC \times VAC,BUS}$$

The transfer switch is located between the inverter output that supplies the AC load and the DG. Its position (i.e., X_S) is thus an operation variable. If X_S = 0, then the inverter is off and the DG supplies all the AC load. If X_S = 1, the DC bus supplies all the AC load via the inverter. X_S falls between 0 and 1when both a parallel inverter and the DG supply the AC load [19].

7. Current Flow

Assessing the currency flow from the various sources to the DC and AC loads while considering the different operating decisions and the efficiencies of the different gadgets along the path helps to determine whether the current electricity supply meets the load demand or whether an imbalance exists between the power demanded and power generated. The primary constraint on the operation is that the current from the generating devices supplied through the system to the load must always equal the requirements of the load. This constraint applies to both the DC and AC loads and is expressed as:

$I_{i,\text{ Supply}} = I_{i,\text{Load}}$;

Where; $I_{i,\text{ Supply}}$ is the DC or AC current reaching the DC or AC load respectively, and
$I_{i,\text{Load}}$ is the DC or AC current needed by the DC or AC load [18].
The AC load can directly be supplied from the DC bus via the inverter or the DG via the AC bus. In this sense, the current supply to the AC load can be put as:
$I_{\text{AC,Supply}} = I_{\text{AC,Bus}} \times (1 - X_S) + I_{\text{Inv-Out}} \times X_S$;
The AC current supply can be expressed as follows when the various sources of currents, i.e., via the inverter and through the AC bus, are substituted accordingly:
$I_{\text{AC,Supply}} = I_{\text{DG}} \times (1 - X_{\text{R,AC}}) \times (1 - X_S) + (1 - X_{\text{R,DC}}) \times (I_{\text{PV,System}} + I_{\text{WT,system}} + I_{\text{HT,System}} - I_{\text{Bat}} + I_{\text{DG}} \times X_{\text{R,AC}} \times \eta_{\text{BC}} \times \frac{V\text{AC}}{V\text{DC}}) \times X_S$

The DC load can be supplied by the current redirected from the DG via the battery charger or from the battery system on the DC bus via the inverter or from the DC renewable energy source. This current can be expressed as:

$I_{\text{DC,Supply}} = I_{\text{DC,Bus}} \times X_{\text{R,DC}}$

When the different sources on the DC are substituted, the DC supply can be expressed as;

$I_{\text{DC,Supply}} = (I_{\text{PV,System}} + I_{\text{WT,system}} + I_{\text{HT,System}} - I_{\text{Bat}} + I_{\text{DG}} \times X_{\text{R,AC}} \times \eta_{\text{BC}} \times \frac{V\text{AC}}{V\text{DC}}) \times X_{\text{R,DC}}$;

A balance between the supply and demands for both DC and AC loads is achieved when the load equals supply, i.e.:
$I_{i,\text{Load}} - I_{i,\text{Supply}} = 0$; [18]

Operation Strategy

The functional decision variables that have so far been identified include the amount of current redirected from the DC bus to the DC load, the quantity of AC redirected from the DG via the battery charger, the transfer switch position, the current output of the battery, and the DG current output decision. The amount of current redirected from the DC bus to the DC load, the quantity of AC redirected from the DG via the battery charger, and the transfer switch position can be determined from the various DC and AC equations as illustrated in the sections above. However, optimizing the current output of the battery and the DG current output at each time constant can be quite laborious because of the computational time, which will call for large numbers of time intervals and reliable and precise weather, as well as demand estimate. It is thus better to have pre-determined control settings that are time-dependent and that relate to the ON and OFF switch of the DG that will be linked to the load demand or the battery state of charge [18, 19].

If the preferred power supply is the DG, then the DG must cover the AC load demand, the uncovered DC load demand, and the battery charger. If the DG cannot fully cover the AC load demand, the DC bus will cover the additional AC load demand via the inverter. If the preferred power supply is the battery system and can cover both the DC and AC load demand, as well as the renewable energy resources, then the battery system can be discharged to a preset level. The DG is, otherwise, chosen as the preferred power source [18].

8. Sizing the Hybrid System and Formulating Control Optimization

The primary goal of sizing the hybrid system and formulating control optimization is to reduce the cost of fuel consumption by the DG during operation time. This function can be expressed as:

$\sum_{j=1}^{N}(al2(\text{DG}j) + bl(\text{DG}j) + c) \times p$;

Where; N is the number of sampling ranges within the system period operation range,
a, b, c are coefficients,
j is the j^{th} sampling interval,
p is the fuel price, and
I_{DGj} is the current output from the DG at the j^{th} sampling interval.
The operation variable limits are;
$0 \leq X_{\text{DG\%}}; X_{\text{R,AC}}; X_{\text{,DC}} \leq 1$;
$X_S = [0, 1]$
The design variable limits are;
$X_i^{\min} \leq X_{ij} \leq X_i^{\max}$

Where; *I* connote the various components of the hybrid system.
The limit of the battery state is given by;
$SOC_B^{min} \leq SOC_{Bj} \leq SOC_B^{max}$; [18].

9. Energy Dispatching Politics

The optimal management of the balance of power among the units producing energy, i.e., the PV field and the DGs, the energy storage unit (i.e., the batteries), and the loads represent the important feature of the system. What optimal management means in this situation is that the power must primarily be sunk from the PV field, which would reduce the intervention of diesel engines. Any excess PV energy is mainly to be stored in batteries, given that they are not in a full state of charge. Such goals, combined with the constraints of the units and other reliability considerations and system dynamics, must be taken into consideration when designing the energy dispatcher. The hybrid PV-diesel energy manager dispatching politics is usually based on integral-derivative regulators, each of which is proportional and with full output [20].
The main battery voltage regulator serves to regulate the charging voltage of the battery and thus intermediate the DC bus voltage in line with the Vbr reference, which is a function of the battery's charge state and temperature. The battery current regulator controls the battery current by regulating the maximum charging current when they are charging in bulk. The generator power regulator caps the current produced by the group diesel engine and flows toward the intermediate DC bus voltage. The energy manager can be faced with several working conditions based on the multiple combinations derived from the state of battery charge, user request, and availability of solar power. These can be simplified into four primary working conditions: i.e., when the battery needs charging (voltage below minimum), and the PV field provides sufficient power; when the battery needs charging, and the power from the PV field is inadequate; when the battery is at nominal charge and power is needed by the loads and so the battery discharge is enabled, and; when the battery is at nominal charge and power is needed by the loads, but the battery discharge is disabled. While the energy dispatcher controls make all the decisions under different conditions, the user may at times, intervene and override the dispatcher controls.

10. Open Issues and Research Scope

The open issues in the planning of a PV-Diesel hybrid system include the voltage level, electrical losses, and diesel operational limits. Concerning voltage levels, [21] explains that electrical power generating authorities are usually mandated to supply electricity to consumers via the grid at a steady voltage (+/- 6% of the nominal). However, this is sometimes only sometimes practical and more so in remote locations because of voltage swells and sags. These disturbances may result from a long distance from a distribution transformer, an unreliable grid system, power distributor tolerances unsuitable for voltage-sensitive equipment, the switching off of large loads, defective local supply equipment, or an unbalanced load on a three-phase system. The disturbances can lead to fluctuations in production rates, the dimming of lighting systems, incorrect functioning of equipment, and unreliable data in equipment tests, among other things. They can be resolved by installing transformers with a tap charger, or the use of a constant-voltage transformer, or a switch mode power supply, connecting larger loads to common coupling points, the use of equipment with deep resilience, the installation of saturable reactors and soft starters on large electrical systems [21].

Regarding electrical losses, some electricity is always lost whenever power is stored in batteries. Moreover, batteries cannot handle too much incoming power; hence, the need for charge controllers. Efficient charge controllers, AC chargers, and inverters minimize power losses from batteries. Further, since power losses are inevitable in all kinds of systems, a system has to produce more electricity than the actual consumed amount [19]. The manufacturers determine the operational limits of diesel generators, on the other hand, and thus it is crucial to select engines that would adequately meet the system's needs. Any misapplication of engine ratings can seriously jeopardize the longevity of a given genset.

11. Design Issues

Some of the design issues of the hybrid controller may include its flexibility to adapt to changes in power consumption, design for non-linear and linear control systems, overcoming the limitations of classical feedbacks using hybrid or nonlinear laws, practical aspects of implementation in hybrid and nonlinear contexts, analytical tools for optimal control of the hybrid system. Alleviating these issues requires a rigorous design approach for the hybrid controller to eliminate all possible defects and meet future challenges.

12. Proposed Network Architecture

The proposed network architecture with the hybrid controller will include three circuit breakers, B1, B2, and B3, to regulate the loads and sources in the network. The hybrid controller's input and control signals will be connected via the Modbus RS485 protocol. The loads are grouped into non-critical and critical types. The latter will be served via uninterruptible power supplies (UPS). The DGs link to the network via the third circuit breaker (B3). B1 controls the utility connection, and B2 contains critical and non-critical segments. The proposed network also has a storage system besides the UPS.

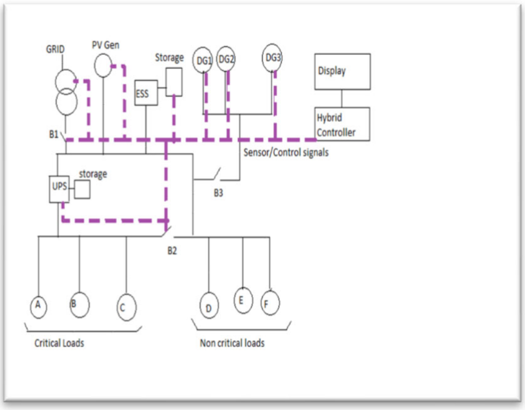

Fig. 1. Proposed Network Architecture

13. Conclusion

In conclusion, this research proposes a robust hybrid controller that can be used as an effective tool in facilitating optimum power sharing between a PV power source and diesel generators based on the dynamics of the available PV energy at any given time. The study has presented the essential functional features of a Hybrid PV-Diesel power station for producing electric energy for a micro-grid from a renewable energy source. The operating modules have been identified to complete a virtual distribution network that can be used for locations that are yet to be reached by an electrical distribution network. The key argument is that the robust hybrid controller that can be an effective tool in facilitating optimum power sharing between the PV power source and the DGs based on the dynamics of the available PV energy at any one time. The framework for the controller has been proposed, including the network architecture and the potential design issues. PV-Diesel hybrid energy systems indeed constitute a significant forward leap in electricity generation.

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