Energy management in a hybrid power system

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***Abstract*—This paper discusses and describes the structure and operation of an energy management system, which is a part of our ongoing research work. In addition, we show the simulation results and the advantages of using an energy management system for an exemplary selected scenario. This management system has the task to meet the voltage and frequency stability criterion in a grid. At the same time, it has to find an economically optimal operation point. The structure of this system is modular and there are a hardware and a software level. This has the advantage that it can react flexibly to the number or installed capacity of power plants, wind turbines or photovoltaic systems.**

Keywords-hybrid power system, energy management system, grid stability, economically optimal operation point.

I. Background Information of Barbados

A. *General information of Barbados*

Barbados is one of several islands in the Lesser Antilles group of the Caribbean. Barbados is approximately 431 kilometers square miles, divided into 12 districts as shown in Fig. 1, with a population of 271,000. The climate in the region is typically tropical, with a constant temperature that rarely descends below 21 degrees Celsius. The island typically experiences a wet season from the beginning of June to the middle of December when the dry season begins and ends at the end of May [1]. In addition, the wet season also brings the hurricane season, which brings either quick or widespread rainfall. However, the island has not been devasted by major tropical depressions within the past decade. There is both a leeward and windward side, with the later located in the trade wind belt. Barbados has a long history in sugar-cane crop cultivation that was once the main source of foreign exchange. Prior to 2009, Barbados as other Caribbean nations benefited from preferential rates paid by the EU for sugar, which was subsequently cut as much as 40 %. The crop generates secure foreign exchange, but at a loss annual [2]. Thereby, supporting the notion to use the industry for an alternative purpose such as energy production.At the moment the main source of foreign exchange and income for the nation is the tourism sector that brings approximately one million visitors to the annually [1].

B. *Reasons for the expansion of renewable energy on Barbados*

For electricity generation, the energy structure was designed over the years to provide reliable, universally available energy resourced at reasonable prices. To date, the island continues to have areliable power supply with few instances of blackouts. There is 100 % access to electricity but remains over 90 % dependent of imported fossil fuel resources for electricity generation and transportation, which is highly unsustainable. As recent as 2015, there was one vehicle for every two persons, which also serves to highlight the importance of electrifying the transport sector [3]. The current fossil fuel mix on the island was summarized as follows: heavy fuel oil (37%), diesel (18%), gasoline (17%), kerosene/jet fuel (7%), sugarcane and other products (3%) and natural gas (2%) [4]. For much of the developed world the utilization of renewable energy has increased due to the sustainability of these resources, lower carbon emissions and mitigating the threat of global warming [3]. However, the main incentive for most Small Island Developing (SID) states is primarily the benefits of cost savings from utilizing domestic renewable energy resources [5]. As other SID nations, the island is particularly vulnerable to declining international reserves, high public debt, a lack of economic diversification and a high reliance on international imports [3]. These financial challenges were further exasperated following the 2008 financial crisis as the price of oil soared to 147 BBDs per barrel, which was the highest in over a decade [5]. The purchase of international oil drains the Barbadian economy of 377 million BBD/annually, resulting in high electricity costs that are passed to the public which will continue without a concerted effort to diversify the energy sector by using renewable energy resources [5]. Although the price dropped in 2013, estimates show the fuel cost alone comprised 0.413 BBD/kWh of the total electricity production costs out of 0.566 BBD/kWh [5].

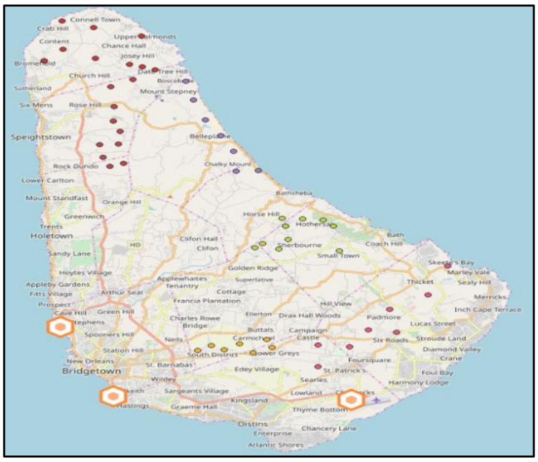

Figure 1. The island of Barbados

C. Solar Resource

The solar resource was the first renewable energy technologies in modern times to be used on a large scale on the island. The average daily solar insolation is 5.7 kWh/m² [6]. This is nearly double to other sites in Europe such as London (2.61 kWh/m²), Dublin (2.39 kWh/m²) and Hamburg (2.52 kWh/m²) [7]. Many of these countries have significantlylarger installed capacities of solar photovoltaics, which serves to demonstrate potentially good solar resources on the island. The solar irradiance peaks during the five-month period of April through August but falls off slightly from August through to December [8]. This trend is in keeping with the rainy season that brings some cloudy to partly cloudy skies and a slight reduction in the solar irradiance. By the latest estimates one out of every five homes on the island uses solar water heaters in addition to most businesses in the commercial and tourism sectors [3]. Presently, more than 95 % of the 30 MW of renewable energy in grid connected systems includes of solar photovoltaics [3]. Regarding scenario development and future studies several recommendations were made for the Barbadian energy system. In assessing a 100 % renewable energy system, an estimated installed capacity ranging between 200 MW – 270 MW was recommended in various scenarios [9]. Similarly, the Barbados National Energy Policy analyzed a 75 % renewable energy mix using 195 MW of installed solar capacity, based on the recommendations of energy sector stakeholders [10].

D. Wind Resource

The wind speeds are shown to range between 4.8 m/s and 8.0 m/s at 10 m hub height, with the lowest wind speeds occurring between August and September [8]. The average hourly wind output follows the hourly demand curve for the island indicating that the peak output occurs midday when cooling demand is at its highest and in the evening when most people have returned home. A total of 472 MW of wind energy may be installed [11]. In Fig. 1 the locations are highlighted by differently colored dots [9]. The model turbine selected from that study was the 2.3 MW Enercon E-70² at a hub height of 75 m. In keeping with best practices no wind turbines less than a 1 MW were selected in order to exploit economies of scale [9]. The main logistical limitations of wind farm installation in Barbados is the lack of infrastructure required for installing large-scale wind turbines and transporting these to some of the areas identified [9].

E. Biomass Resource

The sugar crop is typically harvested from January to May with a total of 258,600.63 tonnes of sugar cane grown from 12,203.00 acres of land [2]. The government of Barbados is planning a 25 MW plant using a combination of bagasse and other biomass residuals [5].

F. Demand and dispatch

As shown in Fig. 1 a total of three generation sites are located on the island of Barbados shown as hexagons. The installed capacities at these locations are follows: Spring Garden (155 MW), Garrison (13 MW) and Seawall (73 MW) [12]. Heavy fuel oil is the cheapest fuel source used by the most of the low speed diesel plants [13]. The peak demand in 2013 was an estimated as 159 MW [3].

G. Pumped-storage power plant

A pumped storage power plant installation ranging from 1 to 5 GWh of storage with an installed capacity ranging from 190 MW – 300 MW is feasible for Barbados [11]. Generally, the island can be considered flat with no extensive mountain ranges, however, one area was identified capable of an altitude drop of between 240 m – 270 m for the upper and lower reservoirs [13].

H. Policy framework of Barbados

The island does have a significant potential for the development of renewable energy and the Government of Barbados has committed to 100 % renewable energy system by 2030. The critical challenge is organization the energy system within the appropriate dispatch of renewable, conventional backup capacity and storage, all of which must be done with financial limitations of the Barbadian economy.

II. FUTURE GRID OF BARBADOS

Table 1 shows the assumed installation capacities of a future grid for Barbados based on the above references. The diesel generators serve as a back-up system to supply the grid with electrical energy when the pumped-storage power plant is empty, and the regenerative energies hardly feed any electrical energy. The installation capacity of the diesel generators is therefore almost equal to the peak load of the grid. The installation capacity of the pumped-storage power plant consists of five Francis turbines. This can allow the feed-in or taking electrical power from the grid. In addition to economic design, the installation capacity is also justified by the fulfillment of the n-1 criterion to ensure a safe and stable grid operation. Table 1 also shows the installation capacities for the photovoltaic system and wind turbines. That seems very large at first, but this is due to the low irradiance from August to December and the low wind speed from August to September. The pumped-storage power plant feeds electrical energy into the grid during this time as long as the reservoir is filled. The diesel generators take over the power supply in an emergency.

TABLE I. INSTALLATION CAPACITIES OF FUTURE GRID

Electrical system	Installation capacities / storage
Peak load	150 MW
Diesel generators	150 MW
Photovoltaic system	180 MW
Wind turbines	180 MW
Pump-storage power plant	250 MW
	3000 kWh

III. CHALLENGES TO MAINTAINING GRID STABILITY

Due to the composition of the installation capacities of the different systems, there are different possible scenarios in the grid.

The operation mode (turbine mode/pumping mode) of the pumped-storage power plant depends on the power difference between the electrical load and the regenerative system. If the power difference is positive and there is more electrical energy available from the regenerative system than currently required, the pumped-storage power plant operates in pumping mode, otherwise in turbine mode. The possible change of the operation mode of the pumped-storage power plant has grave effects on the necessary controller structure. In the turbine mode, the pumped-storage power plant operates in the control mode VF [14]. The same applies to diesel generators. They provide the grid frequency and grid voltage for the regenerative energies operating in PQ control mode. However, if there is a positive power difference due to the weather conditions, the pumped-storage power plant pumps water into the upper reservoir. To keep the grid frequency and grid voltage stable, however, the regenerative energies have to work in control mode VF instead of PQ. The control mode of the regenerative plants therefore depends on the current operation of the pumped-storage power plant. The inverters of the regenerative energies, therefore, require three different controllers (VF, PQ, and synchronization). Via a communication connection, it is possible to change the control algorithm. The structure is exemplarily shown for the active power control in Fig. 2.

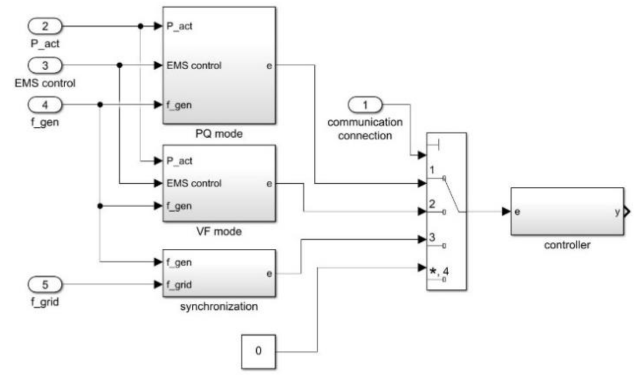

Figure 2. Controller structure of renewable energies

IV. CONTROLLER STRUCTURE OF DIFFERENT POWER PLANTS

There are three levels of regulation: primary, secondary and tertiary. The primary control has the task as fast as possible to respond to frequency and voltage changes in the grid. For this, Droop characteristics are used [15], which result from the requirements of the frequency and voltage quality. If there is, e.g., a failure of a generator, the grid frequency will reduce. Due to the Droop characteristic, all connected generators increase their feed-in power and thus stabilize the electrical grid. The Droop characteristic is located in the subsystem PQ and VF mode, as shown in Fig. 2. In order to replace the primary control power and thus be ready for a possible further generator failure, the secondary control takes over the necessary control power. For this, a PI-controller, shown in Fig. 3, is used, which has an influence on the generated power. It compares the current grid frequency with the setpoint of it. With the aid of the I component of this controller, the grid frequency can be adapted to the setpoint of that frequency in the long term. For the primary and secondary control power, no communication connection to the different power plants is necessary. The Droop characteristic and the secondary controller are located locally. The primary and secondary regulation alone makes the economic operation of the entire Barbados power plant park nearly impossible. The use of an Energy Management System (EMS) enables the long-term economic optimization of the power plant park. The power plant receives a power value sent by the EMS via input *EMS control*, shown in Fig. 2. For example, unnecessary diesel generators can be disconnected through that way from the grid. However, this requires a communication link from the EMS to the different systems. Fig.3 shows the structure for determining the active power setpoint and the control deviation *e* for the PQ mode. The structure for the VF mode regulation is similar. The difference is in the determination of a frequency setpoint instead of the active power setpoint.

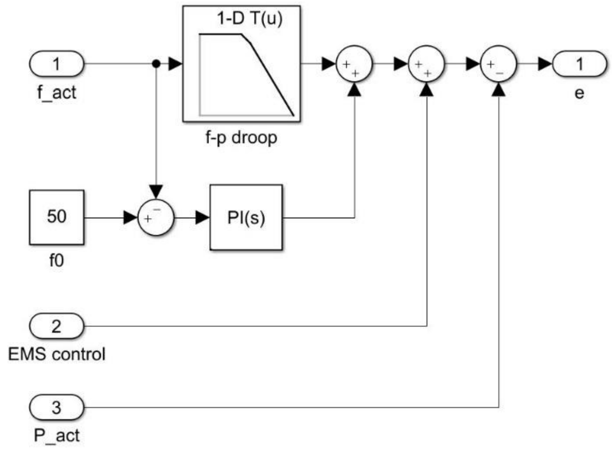

Figure 3. Inside view of PQ mode

V. STRUCTURE OF THE ENERGY MANAGEMENT SYSTEM

The EMS receives important information about, e.g., the level of the reservoir of the pumped-storage power plant, the current weather conditions, the grid frequency, and voltage. With the help of this data, the EMS decides which generating plants should provide how much electrical power or, in the case of the pumped-storage power plant, how much electrical power should be obtain from the grid. Fig. 4 shows the schematic structure of the EMS.

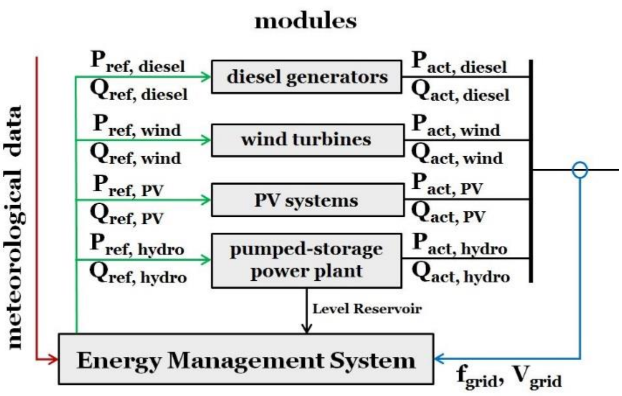

Figure 4. Structure of the EMS

VI. Inside View of the Energy Management System

Fig .5 shows how the EMS performs a power increase in the grid. First of all, any existing power limitations from the photovoltaic converters are reduced so that they feed more electrical power into the grid. Afterward, the power limitations from the wind turbines are reduced so that the fluctuating regenerative energies feed power into the grid as much as possible. The photovoltaic systems have in contrast to the wind turbines no rotating parts and therefore easier to regulate. If the photovoltaic systems and wind turbines feed in almost their maximum possible power (5% reserve) [16] and, nevertheless, more electrical power is required in the grid, the feed-in power of the pumped-storage power plant will be adjusted. When the level of the reservoir from the pumped storage power plant approaches the minimum level, the EMS activates necessary diesel generators to keep the grid frequency and grid voltage stable. If the feed-in power of the pumped-storage power plant is insufficient and the reservoir is still filled, the EMS will also activate diesel generators.

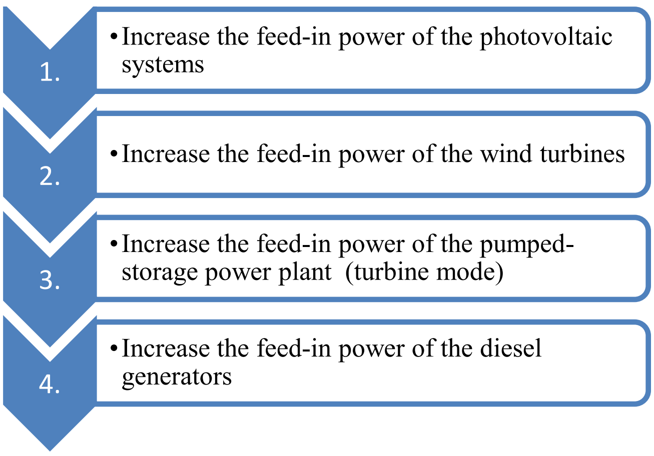

Figure 5. Increase feed-in power by EMS

Fig. 6 shows how the EMS performs a power increase in the grid. First of all, the EMS reduces the feed-in power of the diesel generators because they are the backup-system and only should be used if there are no other sources. The EMS will reduce the feed-in power of the pumped-storage power plant, if there is still a power surplus in the grid. This results in a reduction of the water volume flow out of the reservoir, so that the energy saved is available for later times. The EMS controls the feed-in power of the pumped-storage power plant via the *EMS control* input so that it switches to pumping mode in the event of an existing oversupply of electrical energy. As a result, the level of the reservoir and, consequently, the stored energy increases. When switching from turbine to pumping mode, note that enough regenerative energy converters have to change from PQ to VF regulation mode. That's the task of the EMS to take care about it. If all diesel generators are switched off, all turbine of the pumped-storage system work in pumping mode, and there is still a surplus of electrical energy in the grid, the EMS will decrease the feed-in power of the photovoltaic system. It is better to first regulate the photovoltaic system because they have no rotating parts and thus also incur fewer maintenance costs by correction of the feed-in power. Finally, the EMS also limits the feed-in power of wind turbines in the case of a persistent excess power.

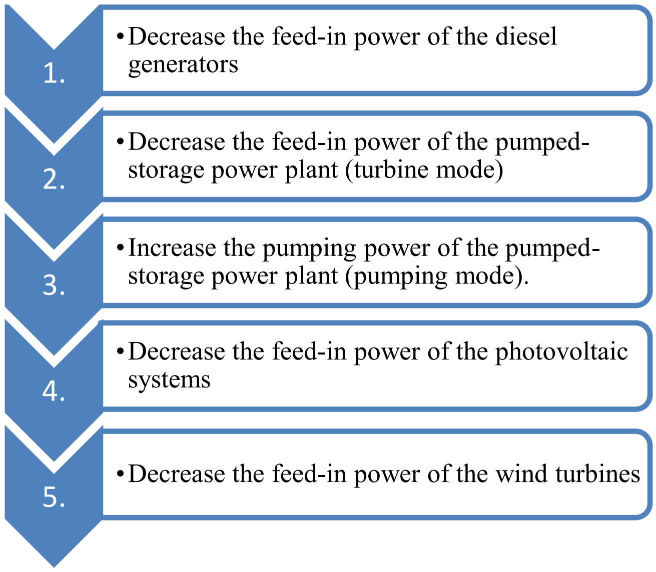

Figure 6. Decrease feed-in power by EMS

VII. Matlab Models for the Different Generating Plants

A. *Pumped-storage power plant*

Fig. 7 shows the structure of one of the five units of the pumped storage power plant [17]. The externally excited synchronous generator is connected to the rest of the grid via the connections L1, L2, and L3. The EMS sends the power setpoint via the input *Pref* to the pumped storage power plant. This value can be positive (pumping mode) or negative (turbine mode).

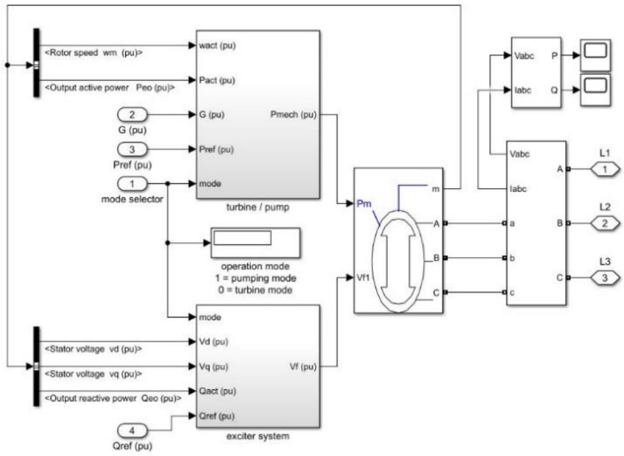

Figure 7. Pumped-storage power plant model

The regulation of the mechanical drive power of the externally excited synchronous generator depends on the selected operating mode. When the pumped storage power plant is in pumping mode, a PI controller determines the valve position so that the power obtained from the grid is equal to the desired reference value. If the pumped-storage power plant is in turbine mode, a PI controller will determine the valve position so that the feed-in power is equal to a reference value. This reference value results from the sum of a Droop characteristic, the secondary control and a reference value received from the EMS.

The control of the excitation voltage depends on the selected operating mode. If the pumped-storage power plant is in pumping mode, a PI controller determines the exciter voltage so that the reactive power obtained from the grid corresponds to the desired value. If the pumped-storage power plant is in turbine mode, a PI controller determines the exciter voltage so that the measured voltage corresponds to the desired reference value. This reference value results from the sum of a Droop characteristic, the secondary control and a reference value received from the EMS.

B. Photovoltaic system and wind turbines

The structure of the photovoltaic and wind turbine model is similar. As shown in Fig. 2, there are three different controls (VF, PQ, and synchronization) within the inverter.

Depending on the currently active mode (VF, PQ or synchronization), the determined reference values for *id* and *iq* reach the current controller, which determines the voltages at the connection ports of the inverter. The structure is shown in Fig. 8 [18].

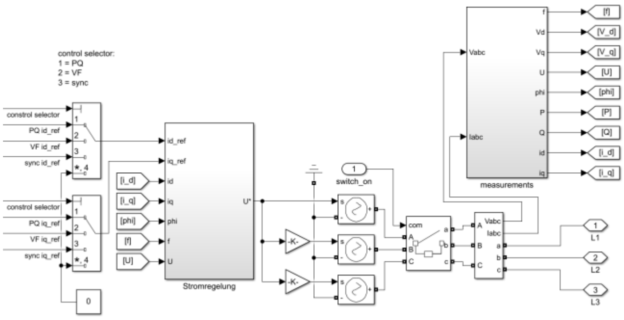

Figure 8. Selection of reference values for id and iq for PQ mode

Fig. 9 shows the structure of the VF control. A PI controller determines the reference currents *idref* and *iqref* from the difference between the reference voltage *Udref* and the currently measured voltage *Ud* or from the difference between the reference voltage *Uqref* and the currently measured voltage *Uq*. The reference values for the voltages *Udref* and *Uqref* result from the sum of the Droop characteristic, the secondary control and a reference value sent by the EMS.

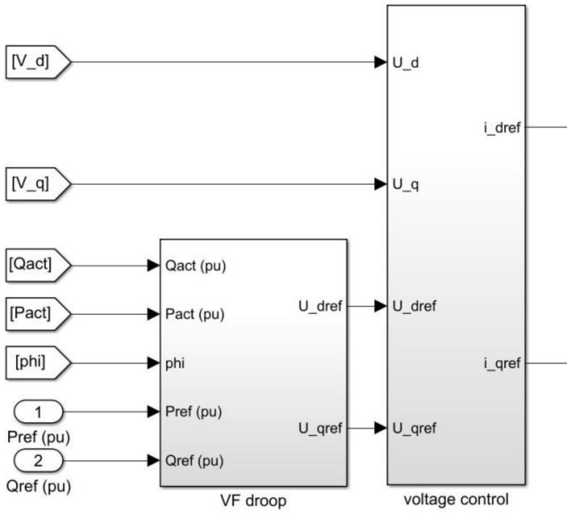

Figure 9. Selection of reference values for id and iq for VF mode

Fig. 10 shows an example of the structure of the PQ control for a wind turbine. The reference value of the active power results from the sum of the Droop characteristic, the secondary control and a reference value sent by the EMS, taking into account the maximum possible feed-in power due to environmental conditions. The reference value for the reactive power results from the sum of the Droop characteristic, the secondary control and a reference value sent by the EMS. The maximum available power results from a power characteristic saved in the model. By changing this characteristic, the photovoltaic systems can be simulated.

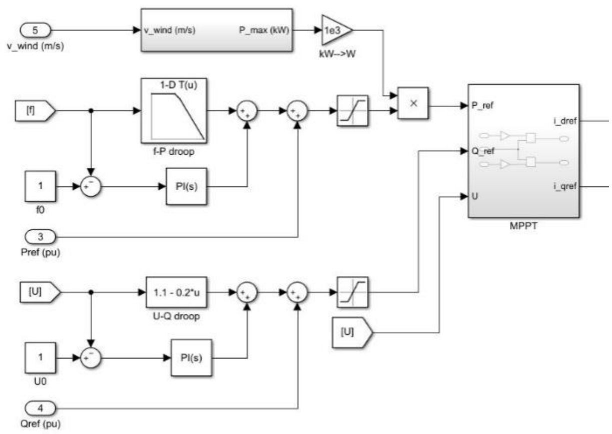

Figure 10. PQ control mode of photovoltaic and wind turbines

C. Diesel generators

Fig. 11 shows the first level of the diesel generator model. The externally excited synchronous generator is connected to the rest of the grid via the connections L1, L2, and L3.

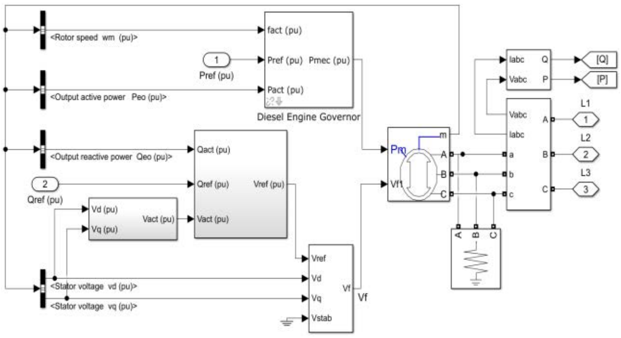

Figure 11. Diesel generator model

Fig. 12 shows the inside view of the model for calculating the mechanical power, which drives the synchronous generator. The behavior of the controller and the internal combustion engine are described by [19]. The setpoint of the grid frequency results from the Droop characteristic, the secondary control and the reference value sent by the EMS. This value, together with the measured grid frequency forms the control deviation to which the controller reacts.

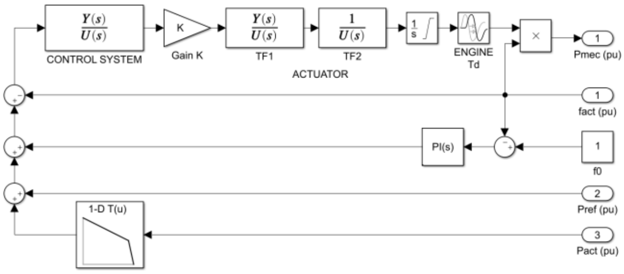

Figure 12. Diesel generator model

The regulation of the excitation voltage receives the measured values of the current-voltage *Vd* and *Vq* and compares them with the desired reference voltage *Vref*, as shown in Fig. 11. Fig. 13 shows the calculation of the reference voltage *Vref* in per unit. It can take values between 1.1 and 0.9 and depends on the feed-in reactive power of the generator, the output of the secondary control and the reference value of the EMS.

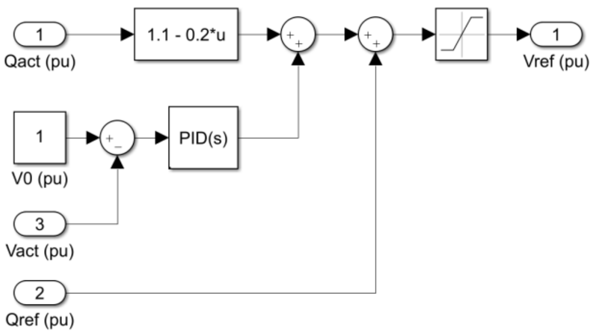

Figure 13. Determination of reference voltage Vref

VIII. Simulation Results for the Selected Scenario

Fig. 14 shows the simulation result for a selected scenario on the island of Barbados. At the beginning of the simulation, the electrical load (P_{load}) is 146.2 MW and at the end 132.1 MW. To get a better overview of the power, the electrical load is also shown negatively. Throughout the simulation, the power factor cos φ is 0.95. Table 1 shows the installation capacities used in this scenario. At the beginning of the simulation, the wind speed is 5.25 m/s, and the irradiance is 180 W/m². The wind speed increases to 7.44 m/s, and the irradiance drops to 90 W/m². Due to the weather conditions, the maximum possible feed-in power of the photovoltaic (P_{PV}) and wind turbines (P_{wind}) increases from 42 MW to approximately 50 MW. The diesel generators feed the power difference between the regenerative energies ($P_{PV} + P_{wind}$) and the demand (P_{load}) for electrical power into the grid. Due to the increasing available power of regenerative energies and the decreasing demand for electrical power, the EMS can disconnect two diesel generators from the grid in this scenario. At the time t_1 = 2700 s, the EMS disconnects the first diesel generator from the grid, which has a nominal power of 11 MW. At the time t_2 = 8000 s, the EMS disconnects the second diesel generator from the grid, which also has a nominal power of 11 MW.

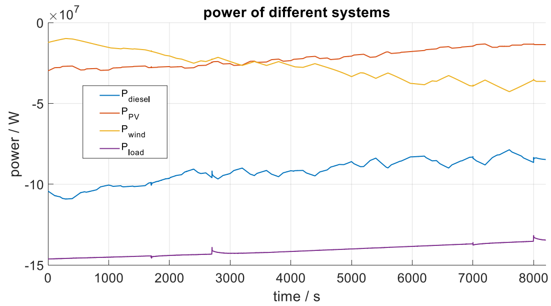

Figure 14. Determination of reference voltage Vref

IX. Conclusion

Barbados currently depends on 90 % of imported fossil fuel resources for electricity generation and transportation, and this results in high costs per kilowatt-hour or a liter of diesel for the cars. The environmental conditions on the island are suitable to extend the previous installation capacity of 30 MW of renewable energies. The long-term expansion of renewable energy sources will increase the independence of fossil fuel resource imports and thus reduce the associated costs. The Government of Barbados has set itself the goal of supplying the island with 100% renewable energy by 2030. This paper shows the necessary structure of the controllers, on the one hand, to maintain the grid stability and on the other to ensure economical operation of the power plant park. Finally, the simulation results show how the EMS disconnects diesel generators that are no longer needed from the grid.

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