# Design of a Power Plant Emulator for the Dynamic Frequency Stability Studies

Erencan Duymaz, Siamak Pourkeivannour, Doğa Ceylan, İlker Şahin, Ozan Keysan

***Abstract* – Increasing renewable energy integration to grid requires inertial support to improve frequency stability of the power system. Inertial support of renewable energy systems requires hardware verification in order to test practical limitations and absence of dynamical grid simulators makes verification studies more challenging. In this study, a test rig which is composed of a DC motor, an AC synchronous generator and an external flywheel, is developed in order to provide a platform in which dynamic properties of an actual power plant can be simulated in the laboratory conditions. A 4 kVA power plant simulator with a field exciter and a speed governor is developed with 1kVA buck converters. The frequency response of the test bench is controlled in parallel with the computer simulations in Digsilent Powerfactory environment. The developed test rig is a low cost and simple solution aimed for experimental studies regarding inertial support of renewable energy systems or power system frequency studies.**

***Index Terms*—Power System Stability, Power Generation Control, Grid Simulator, Power System Dynamics, Frequency Stability**

## I. INTRODUCTION

TOTAL installed capacity of renewable energy systems worldwide has exceeded 909GW at the end of 2017 [1] (excluding hydropower plants). The increase in renewable energy capacity has brought voltage and frequency stability problems for the grid operators. One fundamental problem of the renewable energy systems is the absence of inertial support, which is important to reduce frequency fluctuations in the grid. Fig. 1 shows the variation of frequency in England and Wales for continuous and occasional services. For the continuous service, the frequency is maintained between 49.8Hz and 50.2Hz. If an event occurs in the system, the frequency starts to fall since power consumption is higher than the input mechanical power of the generators. For this period, deficit power is supplied from the kinetic energy stored in the total aggravated inertia of the grid. In order to arrest the frequency decline, primary controllers are activated. However, until the primary controllers take action, frequency decreases linearly from O to X as observed in the Fig. 1. The typical characteristic of the frequency change can be found with the swing equation given in (1) where H is the inertia constant of the generator in seconds, $f_o$ is the frequency value just before the disturbance in per unit, $P_m$ and $P_e$ are input mechanical and electromechanical output powers of the generator in per unit respectively.

$$\frac{2H}{f_o}\frac{df}{dt} = P_m - P_e = \Delta P \tag{1}$$

Conventional synchronous generators have an inherited inertial support capability due to their rotating mass. However, active power generation of the renewable energy systems is not affected from the grid frequency since they are usually connected to the grid via back-to-back power electronics interface. Therefore, replacing conventional generation units with renewable energy systems causes grid inertia to decrease. Synthetic inertia is one solution to overcome the reduced grid inertia which is basically an emulation of synchronous generator behavior using power electronics control techniques. With current expected growth rate of the renewable generation systems, synthetic inertia capability will be necessary for all generation systems which do not have natural inertial support capability [2].

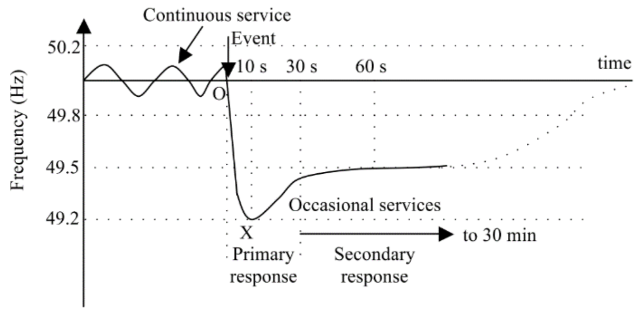


Fig. 1. Frequency control in England and Wales[3], [4]

In order to integrate variable energy resources such as PV and wind energy systems to the power system, significant changes to electric system planning is required to maintain the reliability of the grid [5]. For this purpose, grid simulators are commonly used to test the grid connected inverter performance under grid disturbances. In [6], a grid simulator is proposed based on back-to-back converter with resonant controllers. The designed simulator can generate a range of three-phase voltages with different frequencies. Moreover, the equipment can exhibit unbalanced voltages, harmonic content and flicker. In [7], a back-to-back converter based grid simulator is developed to solve electromagnetic compatibility (EMC) problems. Grid simulators in [8] and [9] are designed for high power applications and they are applicable to Low-Voltage Ride Through (LVRT) studies. However, the frequency of the simulator does not exhibit actual properties of the grid. In [10], a grid simulator is proposed to observe

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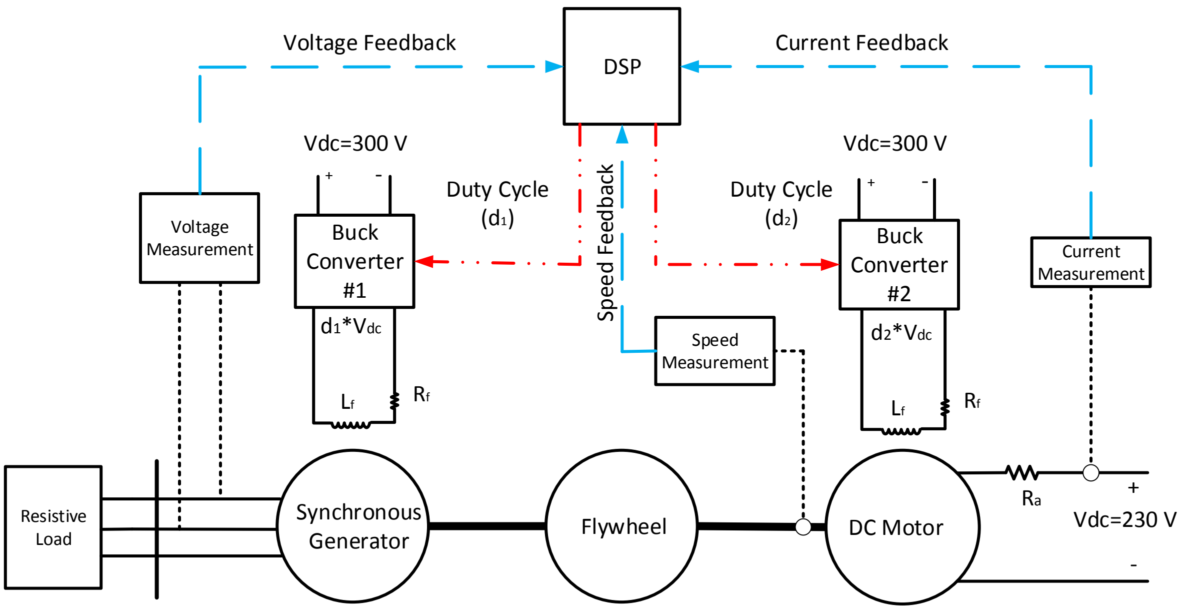


Fig. 2. General description of governor and exciter

system transient performance under voltage disturbances. The study in [11] is based on a novel 9-level series connected H-bridge grid simulator which demonstrates higher power quality waveforms. The design is based on the back-to-back-topology and the design cannot be utilized for frequency stability studies. A novel mechanical power grid simulator is designed in [12] for educational purposes but does not employ real power transmission as in the case of an actual power system. The proposed test setup is based on an analogy between the angular rotation and frequency or voltage. Prime movers are represented by motors that produce mechanical power and loads are represented by DC generators that absorbs mechanical power. They are connected to each other with torsion rods and the grid includes rotational energy rather than electricity. Even though system includes dynamical properties, it is far beyond from an actual power system grid simulator to be employed on frequency stability studies.

Common properties of the grid simulators proposed in the literature are based on back-to-back converters and they cannot demonstrate a realistic frequency deviation. None of the proposed grid simulators has a real inertia that will exhibit the actual grid characteristics in frequency disturbance instants.

In this study, a test rig, which is composed of a DC motor, an AC generator and an external flywheel, is proposed for a realistic implementation of a power plant. Field windings of the AC generator and DC motor are controlled with separate buck converters in order to adjust the AC output voltage magnitude and shaft speed (hence system frequency). The emulated power plant power is 4kVA and generates 380V, 50Hz in the nominal conditions. The main goal of the study is to obtain a realistic frequency disturbance in the grid simulator which is composed of actual synchronous generator coupled with a 1.63kgm$^2$ external flywheel.

## II. System Description

Proposed test rig is composed of a separately excited DC motor, AC synchronous generator (SG) and a flywheel. General description of the system is depicted in Fig. 2. The DC motor is used as the prime mover which emulates the mechanical power input of a power plant turbine. By controlling the field current of DC motor, armature current can be adjusted to desired level since the field current is proportional to back emf and the mechanical power that is delivered to AC generator can be adjusted. A buck converter is used to control the field current and this system is similar to the speed governor of a power plant. Generator speed and hence, the frequency of the output voltage can be regulated by this buck converter. Another buck converter is used to adjust the AC generator output voltage magnitude by varying the field current. The output voltage magnitude is maintained by the exciter action in a real power plant. Note that both AC and DC motor field currents are controlled, instead of controlling the armature currents. This enables the utilization of converters working with lower current values.

### A. *Field Exciter*

For a successful simulation of a typical power grid, the field exciter should be sufficiently fast in order to maintain a constant output voltage. The type of the synchronous generator load is 380V, resistive load. Therefore, it is crucial to have a constant voltage in the generator output. Otherwise, the load power would deviate as the generator speed changes in a step change in the load.

Exciter control diagram is given in Fig. 3 where |V*| is the reference voltage amplitude and |V| is the measured voltage amplitude. Line-to-line output voltage is read by voltage measurement board and it is delivered to DSP analog to digital (ADC) input pin. The required duty cycle of the buck converter is computed in the processor and resultant output voltage applied to the field winding of synchronous generator. Increasing duty cycle will increase the voltage and current applied to field winding. Therefore, control algorithm simply compares the output voltage with the reference voltage value and adjust the duty cycle accordingly.

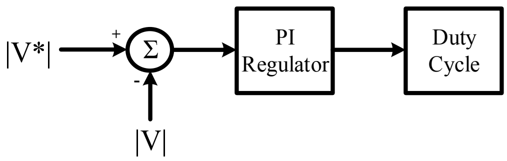



Fig. 3. Exciter control diagram

### B. Speed Governor

Speed governor is a sub-system of a power plant that controls the speed of a turbine. In an actual power plant, the turbine speed is measured and compared with the reference speed. The error is compensated by the governor action. Governor output basically adjusts the mechanical power input by adjusting the steam or water flow rate.

In the plant emulator, DC motor simulates the prime mover. Therefore, it is possible to make an analogy between the DC motor output power and the turbine mechanical power. If the DC motor output power is controlled, then the turbine speed can be controlled as desired. Equation (2) shows the relation between the shaft speed and the net torque. If the net torque is positive, i.e. DC motor output power is larger than the AC output power, then the shaft speed will increase.

$$T_{dc} - T_{ac} = \Delta T = J\frac{d\omega}{dt} \tag{2}$$

In order to have a realistic governor model, the system is constructed with three operating modes.

- Mode 1: System speed is brought to the nominal speed from standstill.
- Mode 2: Input mechanical power is kept constant for a defined time period. This mode is activated simultaneously with load connection.
- Mode 3: Reduction in the system speed due to mode 2 is compensated. The final speed can be either nominal speed or a lower speed.

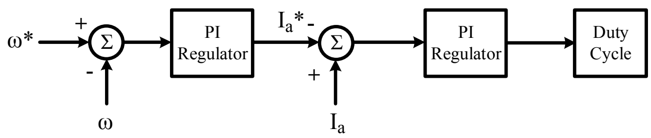



Fig. 4. Governor control diagram for mode 1

In mode 1, system speed is maintained at the nominal speed until the load connection. In order to achieve this purpose, the governor of the simulator receives the speed of the system and the armature current of the DC motor. The control diagram of the governor for mode 1 is given in Fig. 4 where ω and ω* are measured and reference angular speeds in rad/s and $I_a$ and $I_a$* are measured and reference armature currents in A. The comparison of the reference speed and the measured speed determines the armature current reference value. Then, a second comparison is made for armature current value. Note that the armature current of the DC motor is regulated by controlling the field current of DC motor. Due to the fact that duty cycle of the field winding and armature current of DC motor are inversely proportional, increasing field current duty cycle will increase the back emf and decrease the armature current.

There are several advantages of controlling field current. One of the advantages is that low power equipment can be utilized since the field current is in the range of 1-2A. The most important advantage is that controlling field current rather than armature current slows down the system response. This can be observed by considering time constants of armature and field. According to parameters given in Table I, DC motor armature time constant is 12ms meanwhile field winding time constant 124ms. Therefore, more realistic governor model can be emulated by controlling field current rather than controlling armature current.

TABLE I.
DC MOTOR PARAMETERS

| | Resistance(Ω) | Inductance(H) | Time Constants (ms) |
|---|---|---|---|
| Field | 178 | 22 | 124 |
| Armature | 1.15 | 0.015 | 12 |

Control mode 2 is proposed to simulate the time delay of a typical governor response for the frequency disturbances. Since water or steam flow rate cannot be increased immediately in actual plants, the mechanical power that is applied on the turbine will be maintained for a while which in turn results in a decrease on the system speed, assuming a step increase in the load. In order to simulate this accordingly, control mode 2 is proposed. It is based on controlling field current of DC motor to maintain a constant armature current value just before the load connection. In Fig. 5, DC motor equivalent circuit is given. If the armature current is kept constant, constant input power, hence constant output power is achieved in DC motor.

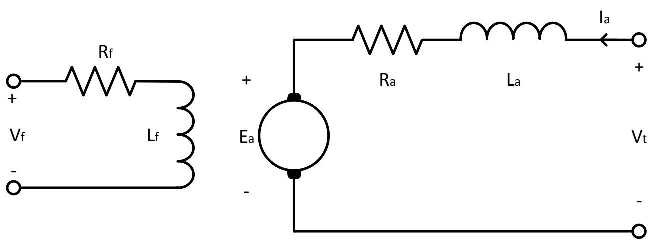



Fig. 5. Separately excited DC motor equivalent circuit [13]

Mode 2 control as presented in Fig. 6 is enabled simultaneously with the step load change. The armature current reference, $I_a$ is the armature current value just before the step change in the load. Keeping $I_a$ constant will keep the input mechanical power of the AC generator constant.

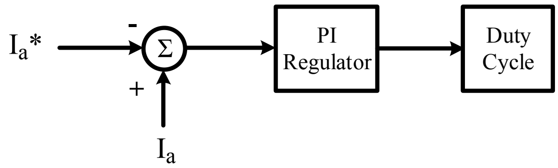



Fig. 6. Governor control diagram for mode 2

Due to the governor delay, the speed and frequency will decrease since there is an unbalance in the input mechanical and generated power. The main advantage of the designed plant emulator is that the speed is decreasing due to the power unbalance in the system, which reflects the actual frequency deviations in the system more realistically.

In mode 3, the generator speed is controlled to recover the system frequency through a PI controller given in Fig. 7. The new speed reference is given to the controller based on the frequency that system converges in simulation results with the same power unbalance. Note that the duty cycle is reduced if system speed is desired to be increased.

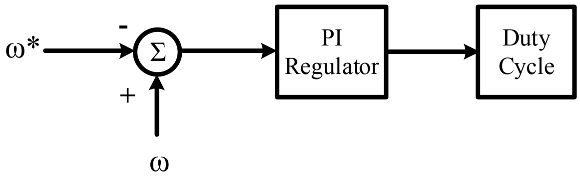



Fig. 7. Governor control diagram for mode 3

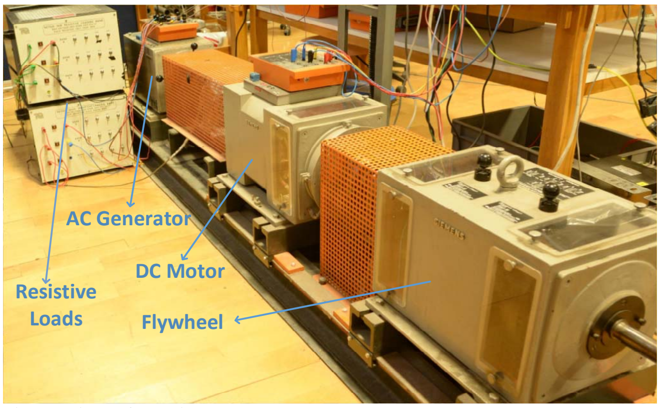



Fig. 8. View of test rig

The plant emulator test rig is shown in Fig. 8. The separately excited DC motor and AC synchronous generator with cylindrical wounded rotor used in the test bench are 4 pole, 4kVA machines. In addition, total system inertia is 2kgm$^2$ with an external flywheel and motor inertia values. The inertia constant of the plant emulator is calculated as 6.16s as in (3) where J is the total system inertia in kgm$^2$, ω is the rated angular speed of the system in rad/s and the $S_{plant}$ is the plant rated apparent power in VA.

$$H = \frac{0.5\,J\,\omega^2}{S_{plant}} = \frac{0.5\;2\;(50\pi)^2}{4000} = 6.16\text{s} \qquad (3)$$

Since the inertia constants of conventional power plants vary in the range of 2-10 seconds [14], inertia of the whole system is sufficient for this study.

When the plant emulator is in steady state in mode 1, 3kW base power is connected to the output terminal of the AC generator. Additional 25% (750W) and 12.5% (375W) step load connections are tested are tested both computer simulation and hardware environments. In the computer simulations, IEEET1 exciter [15] and IEEEG1 governor [16] models are used for the generator. The comparison of the computer simulation and hardware results is presented in Section III. Emulated power plant properties are given in Table II.

TABLE II
PROPERTIES OF THE EMULATED POWER PLANT

| | |
|---|---|
| Generator Power | 4kVA |
| Nominal Voltage | 380V |
| Nominal Frequency | 50Hz |
| Base Load | 3kW |
| Additional Load | 375/750W |
| System Inertia Constant | 6.16 s |

The converter that is used in the plant emulator was initially designed as a full bridge converter, with 600V, 50A IGBT pack F4-50R06W1E3 from Infineon. For this study, the two legs of the full bridge converter have been utilized as two independent synchronous buck converters which are used to excite the field windings of DC and AC machines. Although it is more practical to control directly the armature current of the DC machine in order to control the output power, controlling the field current decreases the power ratings of the switches of the converter since the magnitude of field current is lower than the armature current. Therefore, DC motor field current is used for output power control. TMS320F28335 digital signal processor is used to develop the control algorithm of the system. The frequency and voltage magnitudes are measured with NI-9225 analog input module in NI cDAQ-9178.

## III. Results

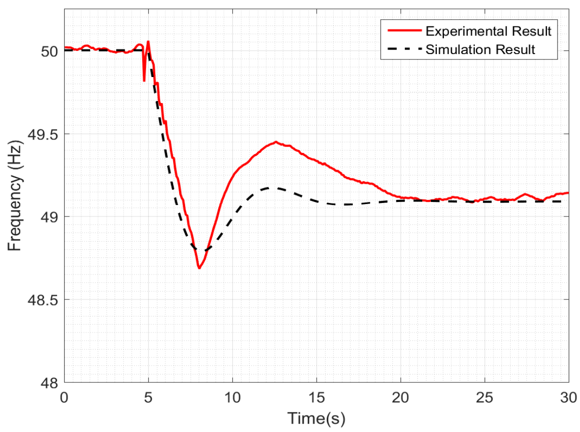
The main objective of the test rig is to obtain a test platform that can be used for dynamical frequency stability studies. Therefore, the pre-disturbance and post-disturbance frequencies are taken from computer simulations and commanded to hardware environment. However, the behavior of the frequency following a disturbance is determined by the system itself depending on the system properties such as the inertia of the system and the size of the disturbance.

In order to validate the test setup, two additional load connections are tested on the system. Until the load connections, test rig is in steady state with 3kW load power.

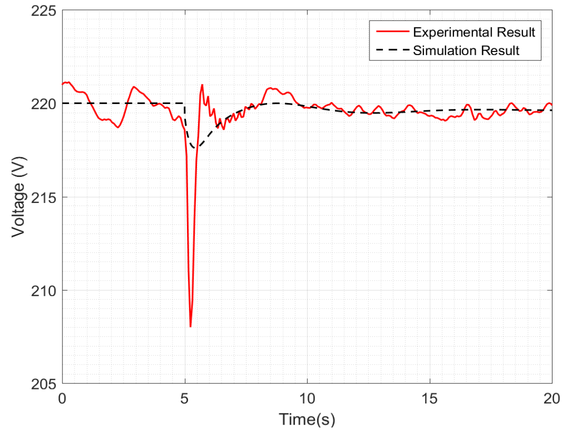
### *A. 12.5% Additional Load Connection*

In the first test case, an additional load of 375W power is connected to system (t=5s). At the load connection instant, system operation is switched into mode 2 that creates a delay in the generation increase. Therefore, the system frequency falls linearly which is given in Fig. 9a. Frequency nadir in the computer simulation occurs (t=8.2) with 48.78Hz meanwhile 48.7Hz at time 8s is achieved in the experiments. Same RoCoF value is achieved following 2 seconds after the disturbance. System frequency goes to the 49.1Hz that is dictated by mode 3.

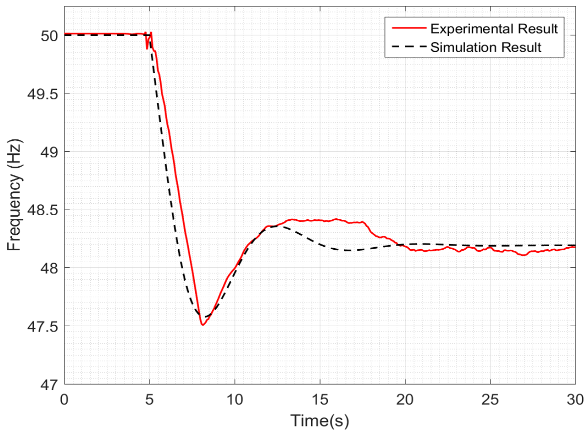
In order to obtain a test rig for the frequency stability studies, test rig output voltage should be regulated. The regulation of the output voltage ensures the power of the additional load. For instance, having a line-to-neutral voltage 220V ensures that added load has a power rating of 375W. The



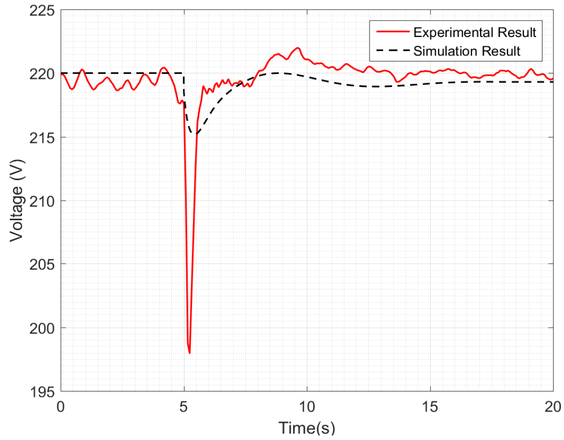

a. Frequency response for the 12.5% additional load connection




b. Terminal voltage for the 12.5% additional load connection




c. Frequency response for the 25% additional load connection




d. Terminal voltage for 25% additional load connection

Fig. 9. Comparison of computer simulations and hardware results

variation of the terminal voltage for 12.5% additional load connection is shown in Fig. 9b. The output voltage of the test rig is maintained around 220V except for the very first instants of load connection. However, the voltage is increased back to acceptable levels 500ms after the load connection thanks to the fast interaction of the power electronics exciter.

### *B. 25% Additional Load Connection*

In the 25% additional load connection case, 750W load is connected to system (t=5s). Fig. 9c shows the frequency response of the experimental results and the results of the computer simulation. Frequency nadir 47.5Hz is achieved in the experiment meanwhile the frequency nadir is 47.6Hz in the computer simulation. System frequency reaches 48.2Hz both in the simulation and hardware.

Variation of the output voltage is given in Fig. 9d. The output voltage is better regulated in the experiments except for the time interval between 5s and 5.5s. However, the voltage is recovered in 500ms by the exciter of system.

## IV. Conclusion

In this study, a 4kVA test rig is developed to be used for dynamical frequency stability studies. The platform is able to provide exciter and governor actions that are served in the actual generators. Frequency nadirs 48.7Hz and 47.5Hz are achieved in the hardware environment with the proposed plant emulation strategy. The frequency of the system decreased according to the system inertia and the size of additional load which was the aim of the study. Although initial and final frequencies are commanded externally, system frequency changes in a realistic way following a disturbance. If a small grid is constructed with proposed plant emulators, power can be dispatched between these plants. In this case, a power reference value and a droop setting can be assigned to the plant emulators. In such a case, there is no need to define final frequency but rather system frequency will reach equilibrium depending on inertia constants and the droop settings.

The plant simulator is designed for the frequency stability studies in which the plant simulator and a power electronics converter interfaced system supply a common load. In this case, plant simulator will be the only conventional generator and the frequency response will be determined by plant inertia. However, if the converter interfaced generation is modified such that it provides inertial response or fast-frequency response, then the improvement in the system frequency can be observed in mode 2 duration. The contribution will change the rate of change of frequency and result in higher frequency nadir in the system.

## V. Future Work

The designed plant simulator will be used to establish a laboratory scale hybrid power generation system whose configuration is depicted in Fig. 10. A wind turbine emulator and a photovoltaic system will supply a common load with the plant emulator. The proposed hybrid generation system will be used to investigate the impact of the increasing renewable energy share in power system. Moreover, synthetic inertia will be studied in the converter interfaced wind turbine emulator for the frequency disturbances. An energy storage can also be utilized in the hybrid system in order to increase primary frequency regulation and also to study generation side management. In addition, the feasibility study of establishing a scaled micro-grid with islanded mode capability and the presence of local active and passive loads will be investigated.

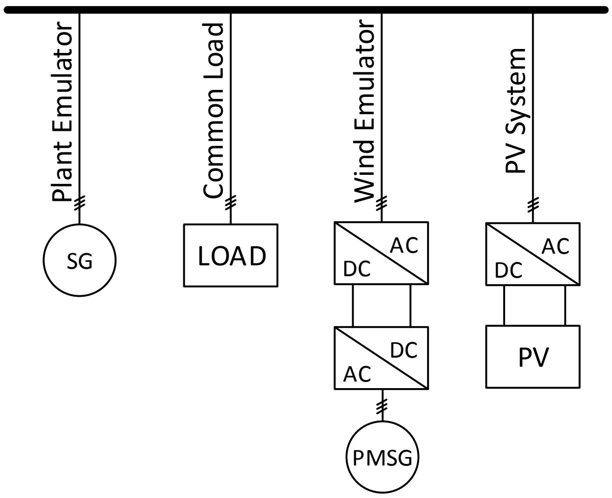



Fig. 10. Hybrid generation system for future applications

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## VII. Biographies

**Erencan Duymaz** received his B.Sc. degree from Middle East Technical University, Department of Electrical and Electronics Engineering in 2016. He is currently pursuing his M.Sc. at the same department in Electrical Machines and Power Electronics area. His main research interests are integration of renewable energy to grid and power system stability.

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