Design of Optimal Real Time Emulators for Steam and Wind Turbines for Avoiding Risky Severe Conditions

helmy El-Zoghby (helmy_028123288@yahoo.com)
Helwan University Faculty of Engineering https://orcid.org/0000-0001-7265-5901
Haitham S. Ramadan
Zagazig University Faculty of Engineering
Hassan Haes Alhelou
Tishreen University

Research Article

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Posted Date: January 4th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1084360/v1

Design of Optimal Real Time Emulators for Steam and Wind Turbines for Avoiding Risky Severe Conditions

Helmy M. El Zoghby[1], Haitham S. Ramadan[2,3], and Hassan Haes Alhelou[4] (Senior Member, IEEE)
[1] Faculty of Engineering, Electrical Power and Machines Dept., Helwan University, Cairo, Egypt.
[2]Faculty of Engineering, Electrical Power and Machines Dept., Zagazig University, 44519 Zagazig, Egypt.
[3]ISTHY (l'Institut International sur le Stockage de l'Hydrogène) 90400 Meroux-Moval, France.
[4]Department of Electrical Power Engineering, Tishreen University, Lattakia, Syria.

Corresponding author: Helmy M.El Zoghby (e-mail helmy_028123288@yahoo.com).

ABSTRACT Modern energy infrastructures may face critical impacts on distributed generation and microgrids in presence of renewable and conventional energy sources. Fast restorations for these networks through proposing convenient proactive protection systems become mandatory for securing energy particularly after severe faults. This paper deals with presenting a descriptive modelling and comprehensive analysis of both steam and wind turbines using optimal real time emulators with unique testbench. Based on the dynamics of each turbine, both emulators are performed using 4kW, 180V, 1500r.p.m separately exited DC motor coupled to 2kW, 380V, 50Hz, 1500r.p.m three-phase synchronous generator. For real-time interface implementation, the mathematical models of steam and wind turbines are realized using LabVIEW™ software. The characterization and verification of both emulated steam and wind turbines are examined at different normal operating conditions in terms of steam valve position and wind speed, respectively. To regulate the current for both systems despite their diverse dynamics, a simple industrial proportional-integral (PI) controller is considered. Unlike other artificial intelligence-based controllers, the offline-controller gains are scheduled using genetic algorithm (GA) via Matlab™ software to ensure the due fast response to cope with unexpected faults. The experimental validity of both emulators is tested at the most severe abnormal operating conditions. The three-phase short circuit is considered at the generator terminals with different fault periods until reaching out-of-step conditions. From numerical analysis and experimental results, the characterization of both emulated steam and wind turbines explicitly mimics their real large-scale turbines in normal conditions. The emulators' fast responses using the proposed GA-PI control approach are verified. Besides, the experimental dynamic behavior convergence and interoperability between the emulated and real systems for both steam and wind turbines are validated under severe conditions. The practical results confirm the fast-nature performance of the GA in avoid risky instability conditions.

INDEX TERMS: ***Modelling*, Steam turbine emulator, Three-phase fault, Validation, Wind turbine emulator.**

NOMENCLATURE

$\delta^{\bullet}$	Rotor angular speed
δ	Rotor angle
P	Active power
T_m	Mechanical torque of generator shaft
Ψ_f	Field flux linkage
μ_{hp}	Steam flow of high pressure
μ_{rh}	Steam flow of reheater
μ_{ip}	Steam flow of intermediate pressure
μ_{lp}	Steam flow of low pressure
μ_g	Governor and interceptor valve positions
T_p	Time constant of low-pressure stage
T_{ip}	Time constant of intermediate pressure stage
T_{rh}	Time constant of reheater
T_{hp}	Time constant of high-pressure stage
T_{iv}	Time constant of interceptor valve
T_{mv}	Time constant of main valve
P_o	Boiler steam pressure
F_{hp}	Power fraction from high pressure stage
F_{ip}	Power fraction from intermediate stage
F_{lp}	Power fraction from low pressure stage
P_w	The rotor mechanical power
V_w	Wind speed at the centre of the rotor
A	Rotor surface
ρ	Air density
R	Rotor radius
C_p	Rotor aerodynamic power coefficient.
λ	Tip speed ratio
C_t	Torque coefficient

I. INTRODUCTION

Synchronous generator, listed among the most efficient machines, converts mechanical movement to electrical energy in different power systems, and typically has more power and ratings besides greater efficiency than other types of generators [1]. Coupling the synchronous generator with steam turbine is known as synchronous turbogenerator [2]. These multi-variable systems are typified with relative high complexity, nonlinearity, and time-variant dynamics [3]. Nowadays, wind farms as a green and renewable source of energy are rapidly growing worldwide with more research studies on their reliably [4-6]. For implementing different studies related to turbogenerators and wind farms, practical and controlled testbench systems are required based on hardware-in-the-loop concept. These systems, mainly implemented inside laboratories, do not depend on the availability of real steam and wind turbines, and enable several tests at normal and abnormal conditions. The testbench of steam or wind energy systems may equip with other mechanisms and devices as: energy storage and

Flexible AC transmission systems (FACTS) devices for enhancing the performance of systems [7, 8].

Steam and wind turbines are complex in nature and expensive. Their weights are relatively large especially for high-rate turbines. Therefore, the turbine emulator is an alternative affordable and applicable approach for verifying practical studies and validating experimental tests under both normal and abnormal conditions. Emulation of these turbines is an alternative convenient option for studying their performance. In [9], the validation of applying the electrical machines emulator has been performed for power converter tests in the development of electric drives. The emulation methodology of the permanent magnet synchronous motor (PMSM) has been proposed in [10]. In [11], the emulation of the electrical machines has been considered based on power hardware-in-the-loop in either motor or generator modes. In [12] a detailed real time emulator for power transformer using Field-programmable gate array (FPGA) has been studied. In [13], a review of the different emulators of solar PV has been studied. In [14], the emulator for small-scale grid using small, distributed generation has been performed.

Implementing the most convenient testbench is necessary for adequately designing, controlling, and establishing new strategies of the emulators of steam or wind turbines. These emulators must reflect the characteristics and the dynamics of real steam or wind turbines [15]. The emulated systems should explicitly mimic the true turbines in producing the same outputs for specific valve positions and wind speeds for steam and wind turbines respectively at different laboratory normal and abnormal conditions [16, 17]. Controlling turbogenerators is due in power systems, since these machines are responsible for ensuring the network's stability, reliability, and security. In [18], the analysis of inter-area oscillations based on govern or position effect and designing the stabilizer in South-Eastern Europe is performed. In [19], studying the performance of turbogenerator system at out of phase synchronization is introduced. Many studies have introduced different control methods concerned with controlling the turbogenerator systems. In [20], designing of two degree of freedom optimal controller for a turbogenerator governor. In [21-23], fuzzy logic controller has been designed for improving the performance of turbogenerator system at different operating conditions.

In case of wind turbine emulation, different studies have explicitly highlighted the importance of emulator's appropriate design. For designing a suitable and efficient emulator for wind turbine, a complete study and identification of the real wind turbine is required considering the linear and nonlinear relations of wind power systems [24-26]. The wind turbine design, types and environmental conditions affecting the turbine modelling and simulation must be considered [27, 28]. In [29], emulation of high rating and inertia wind turbines using smaller machines of lower rates and inertia, the simulation of wind turbines and generators inertia and their effects on power system stability have been presented. The design of turbogenerator stator at high-speed using PMSM has been discussed in [30]. Designing and implementing of an efficient testbench is required for studying the turbogenerator system at different operating condition [31]. The DC machine with either current control or torque compensation loop has been considered for representing the real wind turbine characteristics using Matlab™ software [32, 33]. The verification of the emulator and algorithm has been demonstrated through several tests at step changes in wind speed in [34-36]. In [37,38], the open loop emulator for the wind turbine operation has been implemented using DC machine with FPGA board. In [39-41], the permanent magnet synchronous motor (PMSM) is used for emulating the wind turbine. In [42], the effect of short circuit faults at the generator terminals that driven by the wind turbine have been studied. This type of faults has severely impacted the mechanical and electrical parts of the complete system. During and after clearing these faults, oscillations in electrical power and voltage might occur. Besides, severe vibrations in tower and turbine blades could be witnessed. These oscillation and vibrations might cause system instability and reduce its lifetime.

In [43], the proportional complex integral (PCI) controller has been introduced for enhancing the performance of a grid-connected hybrid power system comprised of wind, photovoltaic and fuel cells. The PCI-based controller has enhanced the system stability, power quality compared to the typical PI controller at normal/abnormal conditions. The PCI controller has removed the oscillations in active/reactive power while eliminating the third harmonics in current signals in addition to eliminating the oscillations in DC link without using a phase locked loop (PLL) in the system.

In [44], a grid-connected hybrid power system of wind, solar and fuel cell has been controlled at maximum power point tracking. Two controllers have been designed to improve the system's performance and power quality (i) PI resonant controller based on stationary reference frame (ii) PI controller based on synchronous reference frame. The former controller cancels the transformations from reference frame to other which leads to simplified mathematical calculations accompanied with PLL reduced errors. The latter controller has provided enhanced power system stability with proper dynamic response at both normal and faulty cases.

Despite the rich literature review concerning the emulation of steam and wind turbines, rare research has considered the validation of both turbines at severe faulty abnormal conditions with a unique testbench, this is the added value of this research. The principal contributions of this paper are the significant characterization of both steam and wind turbines by the same emulator hardware testbench. The proposed testbench experimental architecture can be conveniently used for adequately emulating both Steam and Wind turbines. In addition, the validation of each turbine is confirmed under severe three-phase short circuit at generator terminals until reaching the system's out-of-step point where the system becomes unstable.

In this paper, the fundamental contribution is proposing a simple, fast, cheap, and efficient scheduled-gain PI controllers through optimal genetic algorithm (GA). Accordingly, the current loop in both steam and wind turbines emulators are controlled. The proposed GA-based controllers are mainly responsible for emulating the system and avoiding risky/instability cases. For ensuring the experimental system protection especially during/after severe three-phase faults, fast switch action is vital in presence of faults. For this purpose, the proposed simple GA-based PI controller with optimal scheduled parameters is considered an ideal solution with no time-delay in control signal actions.

The 4kWseparately excited DC motor coupled with 2kW synchronous generator is used for emulating both turbines. Proportional plus integral (PI) controller is implemented using LabVIEW^{TM} software to control the DC motor armature current. The current control loop is responsible for adjusting the controlling voltage required to adjust the instants of the firing pulses through the reliable firing circuit. The firing angle of the thyristors is directly proportional to the controlling voltage level.

Artificial intelligent (AI)-based controllers are considered online tunning. These controllers are mainly developed using neural networks, fuzzy logic, neuro-fuzzy or other approaches. Although the AI-based controllers can provide system performance enhancements in normal operating conditions, their slow-action and time-delay because of training to ensure the adaptive tuning are still a major drawback. In real time intelligent regulators, the control signals may suffer from undesired time-lag characteristics compared to conventional PI controllers. For this reason, the AI-based control is not considered the ideal option to deal with severe three-phase short circuit faults at generator terminals. In such a case, fast control actions are due. The GA-based PI controllers provide a favored compromise between efficiency, simplicity, and affordability in comparison with intelligent-based alternatives particularly under sever risky operating conditions. Therefore, in this paper, the GA, as efficient and fast offline approach, is considered for the optimal scheduling for the simple PI controller gains. The PI controller is used in the inner current controlled loop in the emulator software program to force the DC machine torque to be the same as the real turbine torque [45].

The experimental validity of both emulators is tested at the most severe abnormal operating conditions. The three-phase short circuit is considered at the generator terminals with different fault periods until reaching out-of-step condition. The optimized controller gains are used in the LabVIEW^{TM} program to control the firing circuit that feeds the separately excited DC motor.

The novelty of this research compared to the existing studies is: (i) implementing a real-time unique testbench that successfully emulates two different systems (steam and wind turbines) of inherent particular characteristics and diverse constraints, (ii) applying a simple and affordable PI controller with adequate fast response where its parameters are offline-scheduled using genetic algorithm (GA), (iii) verifying the applicability of the proposed testbench for emulating two proposed systems of different dynamics and its suitability at normal operation and abnormal severe critical cases that may result in undesired system instability, (iv) applying several severe tests using the proposed testbench that should not be employed to real turbines for keeping them protected.

In this paper, steam and wind turbines emulators are mainly designed for controlling, protection and condition monitoring of both real-sized turbines. The proposed unique testbench provides less expensive and scalable interface that enables the optimal control, an efficient proactive protection, and data monitoring of the critical energy sources in real-time conditions.

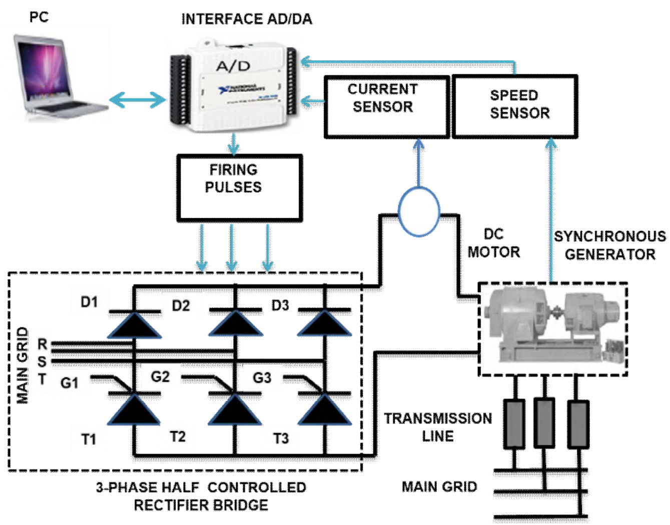
The innovative features of the architecture of the proposed testbench are mainly in its simplicity, applicability, and suitability for emulating both steam and wind turbines. The particularity of this unique structure with defined components is its convenience for both turbines of different dynamic performance, inertia, and nonlinearity degree. The software program modification is considered to represent the varied dynamics of these turbines.

The rest of this paper is organized as: In Section II, the emulated system structure, design, and problem formulation is discussed. In Section III, the practical testbench structure is discussed. In Section IV, a full study of steam and wind turbines dynamics and modelling is presented. In Section V, the characterization of the steam and wind turbines at normal operating conditions is presented. In Section VI, the validation of the steam and wind turbines while considering the sever three-phase fault condition at the generator terminals is discussed. Finally, in Section VII, the conclusions and perspective of this research are highlighted.

II. PROBLEM FORMULATION AND THE PROPOSED TESTBENCH

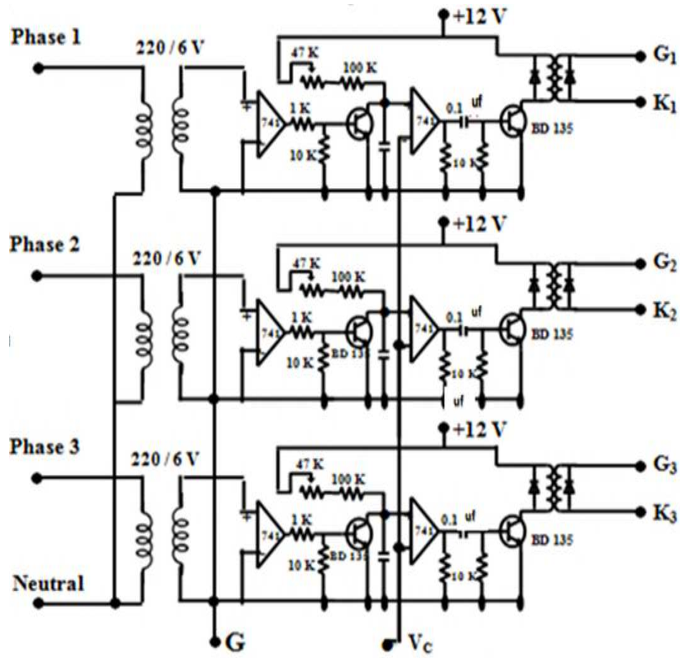
Applying and verifying novel optimized control techniques for practical real steam and wind turbines are difficult because of their relative high costs and weights. In this research, real time emulators with unique testbench are suggested instead of using real turbines. The proposed emulators enable characterizing both turbines at different normal/ abnormal operating conditions and avoiding risky instable cases.

For real steam and wind turbines, the emulator design and implementation are presented using the same testbench configuration and circuits. The complete block diagram of the testbench is shown in Fig. 1. The system includes the DC motor that emulates the turbine dynamics and characteristics. The DC motor is coupled with three-phase synchronous generator. This latter is connected to the main grid through short transmission line. The DC motor current is controlled using three-phase half-controlled thyristors bridge of three diodes and three thyristors as shown in Fig. 1. a. The thyristors bridge pulses generated from the firing circuit that controlled using PC computer with interfacing data acquisition (DAQ) cards on LabVIEW™ environment. As shown in Fig. 1.b, the firing circuit consists of three identical branches; each one is connected to one phase of the Thyristors Bridge. Each circuit can control the pulse position from 0^0 to 180^0 of the positive periods of each phase.



a. The testbench valid for steam and wind turbine emulation.

Efficient and calibrated sensors is used for measuring the DC motor speed by tachometer device and armature current. The fault period is adjusted online using LabVIEW™ program and a control signal trips a three-phase contactor to close the three terminals of the generator making three-phase short circuit. The Simulink model is impeded in LabVIEW™ program for controlling the real time system and recording different measurements. Real time DAQ cards are used for interfacing the PC computer to the system. From the measured motor current, the firing pulses are calculated and continuously controlled until the actual motor torque equal the reference torque that calculated from the turbine dynamics. From the measured rotor speed, the frequency is calculated especially for off-grid connection or abnormal cases.



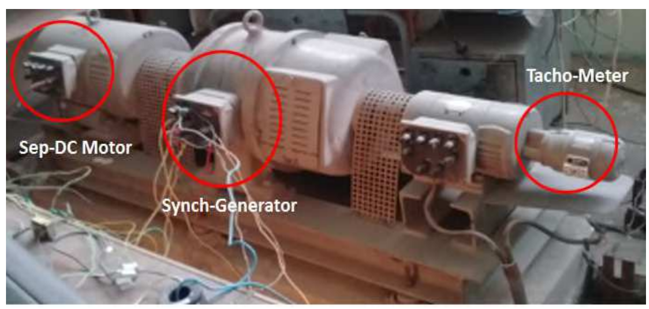
b. Three phase firing circuit.

Fig. 1. The proposed testbench of steam and wind turbines emulator and its firing circuit.

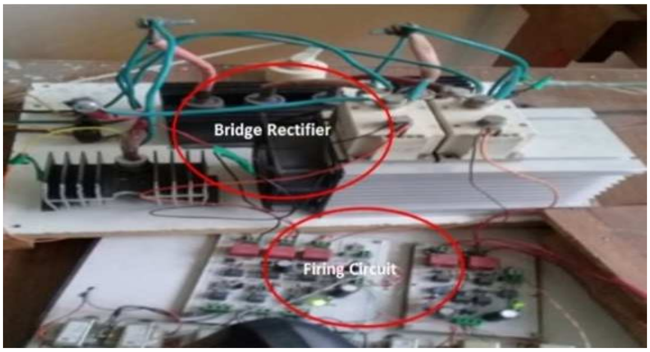
III. LABORATORY TESTBENCH ARCHITECTURE

Fig. 2 is a photograph of the proposed practical testbench that used for implementing the emulator for both turbines. In Fig. 2.a, the motor-generator set used in the experimental model is depicted. The motor current is controlled by adjusting the instants of the firing pulses of the half-controlled three-phase Thyristorized Bridge. The bridge is composed of three thyristors and three diodes with three-phase firing circuit as illustrated in Fig. 2.b.

The single/three phase-controlled rectifier circuits, mainly thyristor-based, may be either half or full controlled. In this study, the three phase-controlled rectifiers with six pules and half controlled is considered. The proposed circuit has three diodes and three thyristors and requires only three control signals. This requirement simplifies the controlling programs and the relevant isolation circuit configuration as shown in Fig. 2.b.



a. Photograph of the motor-generator set.



b. Photograph of the firing circuit and the controlled rectifier bridge.

Fig. 2. Practical testbench used for emulating steam and wind turbines.

IV. STEAM AND WIND TURBINES DYNAMICS

Testing real steam and wind turbines in the laboratory is so difficult due to their higher weight and cost. Based on the dynamics of each turbine, the simulation model is established in Matlab™. The Simulink models are used in the LabVIEW™ program during the different testes that characterized and validated both turbines. The fundamental challenge is to validate a testbench with unique architecture for emulating two systems with different characteristics, dynamics, non-linearity degree and operating modes. The steam and wind turbine models are of thirteenth and forth order, respectively. While the former is a conventional turbine and still in use so far, its operation is mainly based on conventional energy resources (diesel, coal, gas, …). The wind turbine operation, as a renewable energy source, has shown notable growth rate in implementation, industry, installation, and research. The proposed testbench is succeeded in emulating both diverse turbines at different operating conditions. Besides, the emulation at unstable operation is illustrated because the difficulty of testing these conditions for real turbines.

Both models of steam and wind turbines are nonlinear and accurate models based on [45] and [46] respectively. For the steam turbine of this study, the three-stage structure is considered where one of these stages is high pressure and the others are low pressure with single reheater. This latter is modelled as first orders transfer function. However, the wind turbine design is a horizontal axis and three blades.

A. Steam Turbine Dynamics

In this work, the synchronous generator is driven by three-stage steam turbine with single reheater. The turbine is represented by thirteenth order nonlinear model. Any stage of the turbine stages is represented by a first order transfer function with single time constant. The stage output is weighted based on its sharing in the overall output torque. The reheater and governor valve servomechanisms are considered as first order transfer function. The steam turbine equations that describe its dynamics in the state space form are [46]:

$$S=[S_1\ S_2\ S_3\ S_4\ S_5\ S_6\ S_7\ S_8\ S_9\ S_{10}\ S_{11}\ S_{12}\ S_{13}]= [\delta\ \dot{\delta}\ \psi_f\ \psi_d\ \psi_{kd}\ \psi_q\ \psi_{kq}\ \mu_{hp}\ \mu_{rh}\ \mu_{ip}\ Y_{ip}\ Y_{mv}\ Y_{iv}] \quad (1)$$

$$P\mu_{hp} = \frac{(P_o.Y_{mv} - \mu_{hp})}{T_{hp}} \quad (2)$$

$$P\mu_{rh} = \frac{(\mu_{hp} - \mu_{rh})}{T_{rh}} \quad (3)$$

$$P\mu_{lp} = \frac{(\mu_{ip} - \mu_{lp})}{T_{lp}} \quad (4)$$

$$P\mu_{ip} = \frac{(\mu_{rh}.Y_{iv} - \mu_{ip})}{T_{ip}} \quad (5)$$

$$PY_{mv} = \frac{(\mu_g - Y_{mv})}{T_{mv}} \quad (6)$$

$$PY_{iv} = \frac{(\mu_g - Y_{iv})}{T_{iv}} \quad (7)$$

$$T_m = F_{hp}.\mu_{hp} + F_{ip}.\mu_{ip} + F_{lp}.\mu_{lp} \quad (8)$$

From Equations (2) to (8) for the synchronous generator and the steam turbine, the Simulink model for turbogenerator system is constructed as in Fig. 3. The model inputs are the governor position (Ug) and mechanical power (Pm), the model output is the mechanical torque (Tm). The overall transfer function of the turbogenerator system is thirteen orders.

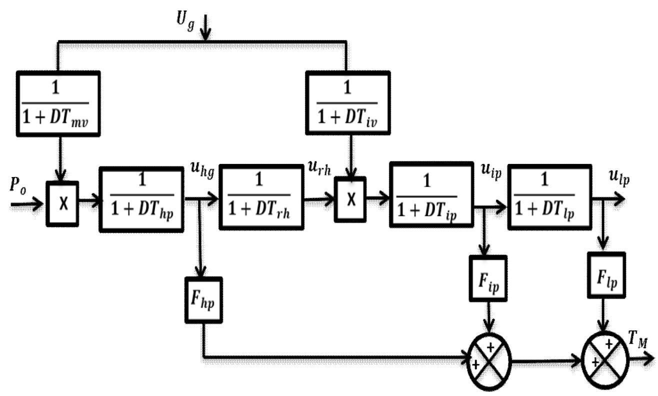


Fig. 3. Turbogenerator system block diagram.

B. Wind Turbine Dynamics

Extracting electrical energy from wind energy is a complicated process. The energy captured from wind is converted to mechanical energy by the turbine blades. The mechanical energy is converted to electrical energy by the generator coupled to the turbine shaft [47,48]. The turbine output power depends on the wind speed value, blades area and design of the turbine [49]. The complete model of the wind turbine considering all variables and constrains is required for facilitating the study of the wind turbine characteristics [50]. The turbine's simulated model with the dynamics will simplify its characterization and the validation of the turbine at any operating condition [51]. The different equations that describe the wind turbine dynamics are:

$$P_w = \frac{1}{2}\rho C_p(\beta, \lambda_i) A V_w^3 \tag{9}$$

where P_w refers to the rotor mechanical power (W), V_w expresses the wind speed at the center of the rotor (m/s), $A = \pi R^2$ denotes the rotor surface (m^2), R is the rotor radius (m). ρ refers to the air density (kg/m^3). C_p is the rotor aerodynamic power coefficient.

$$\lambda_i = \frac{1}{\frac{1}{(\lambda + 0.08\beta)} - \frac{0.035}{(\beta^3 + 1)}} \tag{10}$$

where λ refers to the tip speed ratio of the blade if its pitch angle is constant and defined as:

$$\lambda = \frac{R\,\omega_R}{V_w} \tag{11}$$

Considering the torque coefficient $C_t(\beta)$, the wind turbine mechanical torque is given by:

$$T_w = \frac{1}{2}\rho R^3 V_w^2 C_t(\beta, \lambda_i) \tag{12}$$

$$C_p(\beta, \lambda_i) = \lambda C_t(\beta, \lambda_i) \tag{13}$$

The dynamic equations (9) to (13) describe the wind turbine characteristics. From these equations, the Simulink block diagram of the wind turbine is established as in Fig. 4. This diagram is used in the real time LabVIEW™ program for emulating wind turbine.

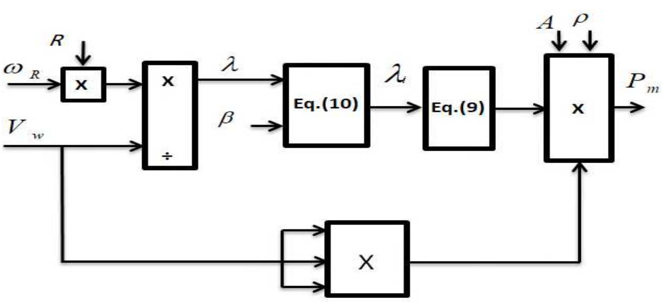


Fig.4. Wind turbine block diagram.

The experimental tests are performed using the proposed testbench in Sections V and VI, respectively. The steam and wind turbines are characterized using the real-time emulator to demonstrate its capability in characterizing the real turbines at normal operating conditions. Different tests under normal operating conditions are performed while assuming various changes in steam valve positions and wind speed for steam and wind turbines, respectively. Then, the experimental validation of steam and wind turbines under severe faulty conditions are confirmed using the real time emulators for the unique testbench.

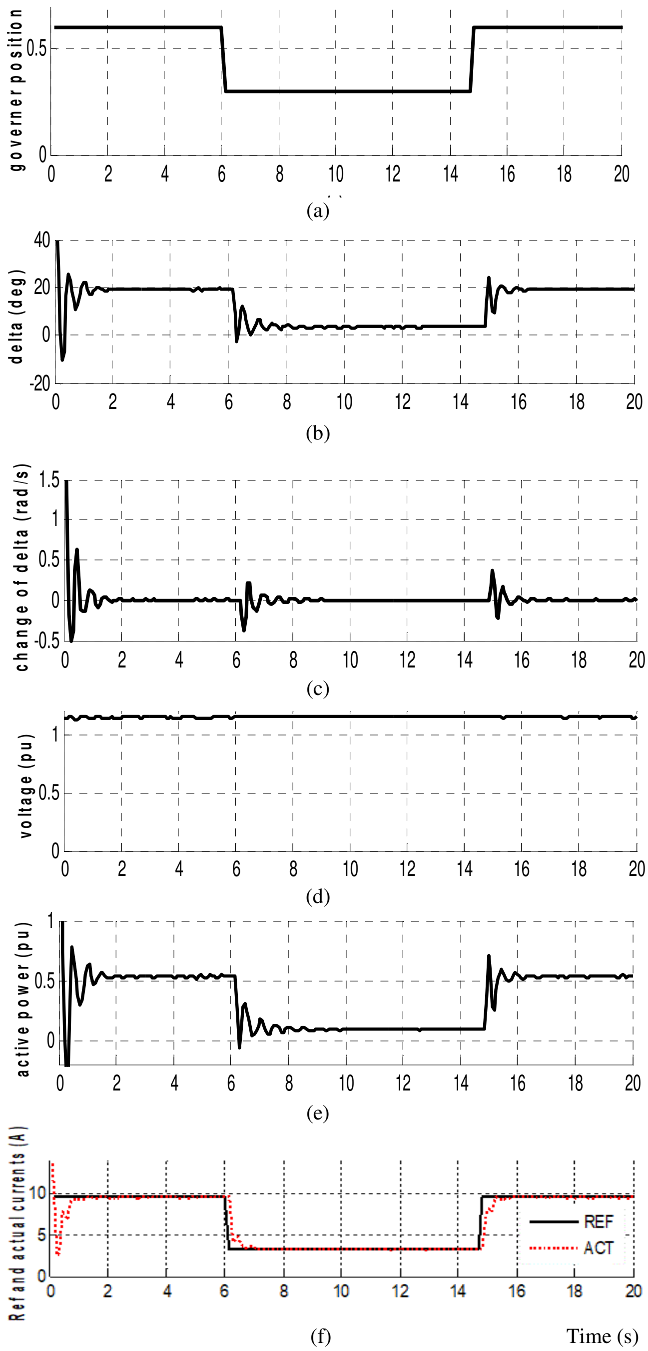
V. CHARACTERIZATION OF STEAM AND WIND TURBINES

The proposed experimental steam and wind turbines emulator is characterized to demonstrate the effectiveness of the emulator for characterizing the real steam and wind turbines. Different tests at different normal operating conditions are performed in terms of several changes in steam valve positions for wind turbine and wind speed for wind turbine.

In this work, the proposed separately excited DC motor is used for emulating the characteristics of both steam and wind turbines at different operating conditions. Based on the value of the steam valve positions for steam turbine or the value of the wind speed for wind turbine, the LabVIEW™ controlling program calculates the motor reference current. Therefore, the motor actual armature current is controlled to track the calculated reference current using current control loop with simple PI controller. The rotor speed is constant due to the connection of the coupling synchronous generator to the main grid. Three phase half-controlled rectifier bridge is used for controlling the armature of the DC motor, the firing pulses of the circuit generated from the operating program based on the reference current and out to the real world using interfacing DAQ cards.

A. Steam Turbine Characterization

The proposed emulated three-stage steam turbine is implemented and tested to validate its ability to behave as the real steam turbine. Therefore, the constant governor valve position of 0.6 pu is proposed. The generator field voltage is adjusted until grid synchronization. Fig.5 demonstrates the performance of steam turbine emulator considering step changes in governor position. The governor valve position was initially at 0.6 pu and changed to 0.3 pu and then 0.6 pu as depicted in Fig. 5. a. The rotor angle (delta) oscillates due to changes in the steam valve position and returns to steady-state condition as illustrated in Fig. 5. b. The rotor speed oscillates with changing the steam valve position and returns to steady state as depicted in Fig. 5. c. The terminal voltage of the generator is almost constant due to the connection to stiff grid of constant voltage and frequency as shown in Fig. 5. d. The active output power of the generator is shown in Fig. 5. d. The reference and actual armature current of the DC motor are demonstrated in Fig. 5. e. The reference and actual currents have adequate tracking. The DC motor tracks the steam turbine dynamics. From Fig. 5, it can be concluded that the steam turbine emulator characterization adequately mimics the real steam turbine behavior while considering steam valve position variations. Zero steady-state error and short rise time are reached.

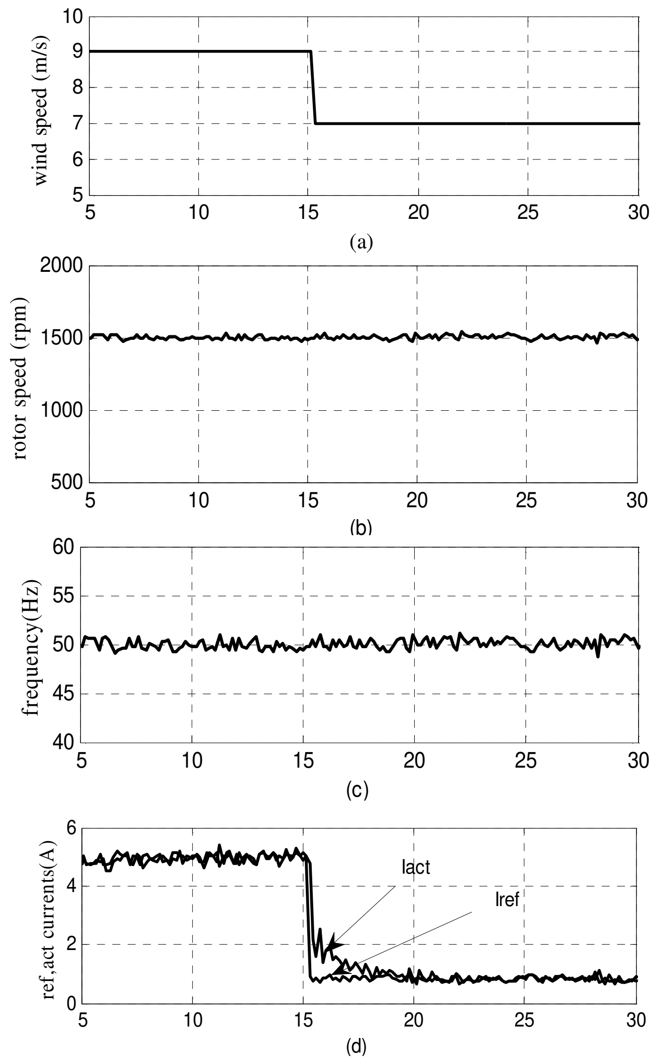


(a) (b) (c) (d) (e) (f)

Fig. 5. Performance of steam turbine emulator at step changes in governor position.

B. Wind Turbine Characterization

The emulation of wind turbine using DC machines of low power and inertia using efficient software programs is the research trend [51,52]. Different control techniques are used with wind turbine emulator to assure its characterization besides the experimental validation of the real wind turbine [53-56]. Both model predictive and optimal control techniques have been witnessed for controlling wind turbines under various operating conditions [57,58]. Different metaheuristic-based optimal control techniques have been used for controlling a wind turbine driving DFIG in [59] and several experimental tests have been illustrated in [60]. In this study, the separately excited DC motor is considered for emulating the characteristics of the wind turbine. Using LabVIEW™ software program, the motor current is adjusted to reach the same active power of real turbine under any changes in wind speed. Fig. 6 displays the performance of the wind turbine emulator considering sudden step-down in wind speed. The wind speed stepped down from 9m/s to 7 m/s as shown in Fig. 6. a. Due to the connection of generator to stiff grid of constant frequency and voltage, the generator speed and frequency are constant as in Fig. 6.b and Fig. 6.c respectively. Fig. 6.d shows the adequate tracking of the emulated turbine current and its corresponding value of the actual DC motor. Since the wind speed is stepped down, the output power is accordingly decreased from 1100 W to 200W as depicted in Fig. 5. e. The output torque reduction from 7 N.m to 1 N.m is illustrated in Fig. 6. f. Fig. 6.g shows the dynamic behavior of the controlling voltage (Vc) that enables adjusting the firing angle of the converter circuit.



(a) (b) (c) (d)

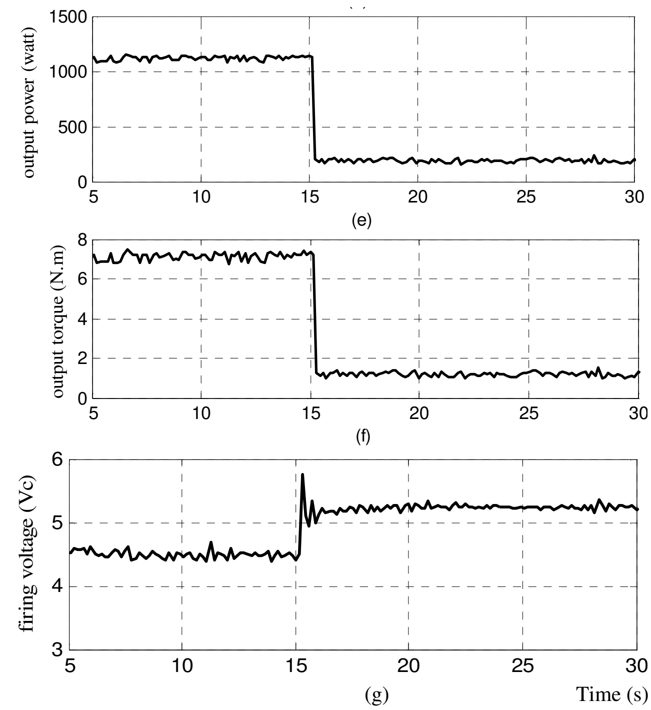
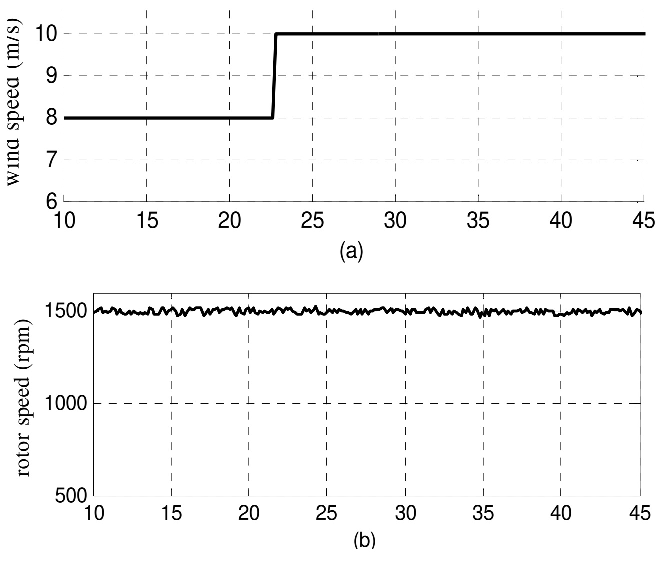


Fig. 6. Performance of the wind emulator at step-down in wind speed.

Fig. 7 displays the dynamic performance of the wind turbine emulator with sudden wind speed step-up. The wind speed stepped-up from 8 m/s to 10 m/s as shown in Fig. 7.a. As the generator is connected to stiff grid of constant frequency and voltage, the generator speed and frequency are constant as in Fig. 7.b and Fig.7.c respectively. Fig.7.d shows the adequate tracking of the emulated turbine current and its corresponding value of the actual DC motor. Since the wind speed is stepped up, the output torque increases from 4 N.m to 11.5 N.m as displayed in Fig. 7e. The output power is consequently stepped up from 550 W to 1800 W as shown in Fig. 7. f. Fig. 7.g shows the firing voltage (Vc) that controls the firing angle of the converter during the tracking process.



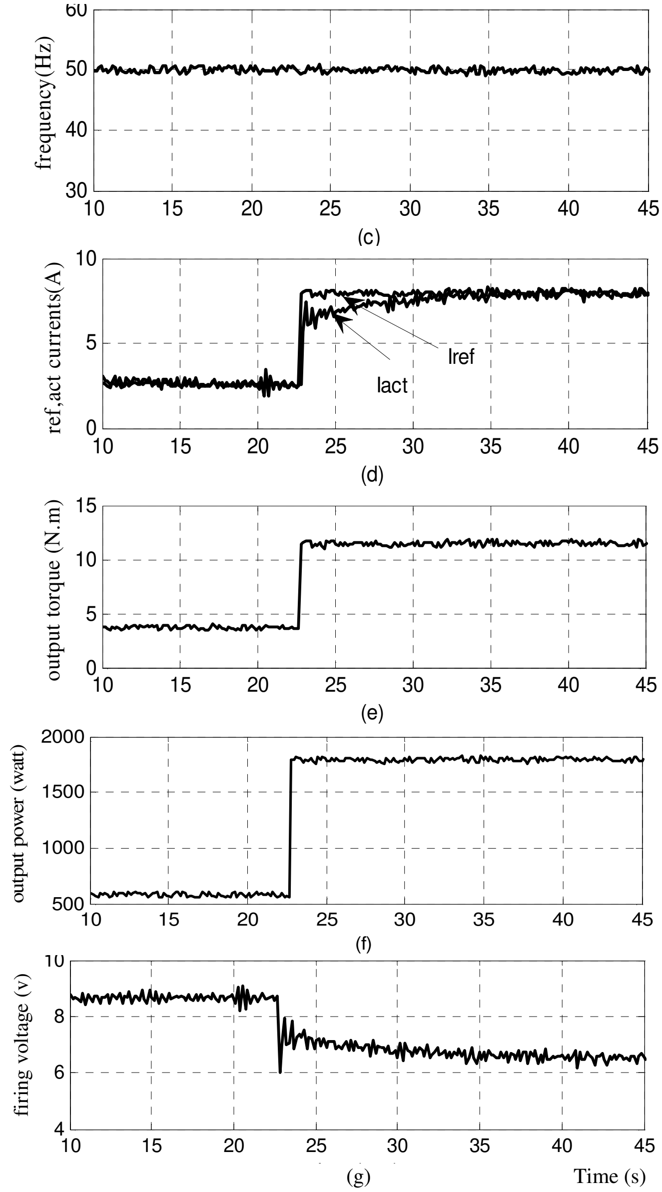


Fig. 7. Performance of the wind turbine emulator at step-up in wind speed.

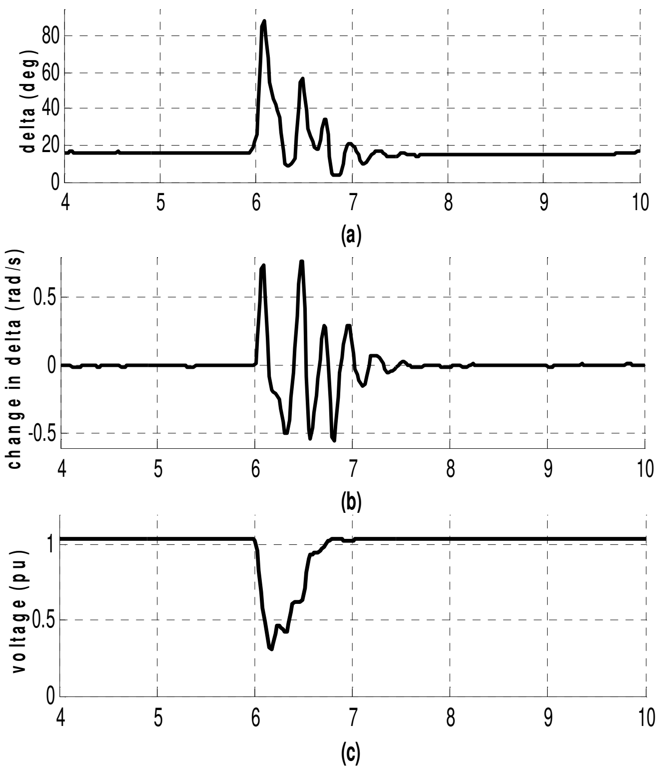
It can be noticed that the difference between current tracking convergence time in Fig. 5.d and Fig. 6.d is directly related to the various dynamics and modelling characteristics of steam and wind turbine, respectively. The faster convergence time of the current tracking process is mainly due to the fast response in wind turbine dynamics, which is not the case in the steam turbine that based on three stages steam turbine (one high and two low pressure stages) with single reheater. In Fig. 6.d, the wind speed is stepped down. Accordingly, the tracking process takes less time. The generator loses kinetic energy. However, in Fig. 7.d, the wind speed is stepped up. The relevant increased tracking time is required to overcome the moment of inertia of the rotating parts. The generator gains more kinetic energy.

VI. EXPERIMENTAL VALIDATION OF STEAM AND WIND TURBINES AT SEVERE FAULT CONDITIONS

For illustrating the added value and the main feature of the proposed real-time emulator, the practical validation of the proposed steam and wind turbine emulator at severe fault conditions is studies. The experimental validation of both turbines is recorded at three-phase short circuit at the generator terminals considering different faults durations attaining the system's out-of-step at which the system becomes unstable.

A. Validation of Steam Turbine Emulator

Fig.8 is the performance of the turbogenerator system during and after three-phase short circuit at the generator terminals for 80 ms. Constant governor valve position of 0.5 pu and an exciter voltage of 3 pu are applied to the system. The power angle delta is shown in Fig.8. a. The rotor speed variation is in Fig. 8. b. The terminal voltage of generator is shown in Fig. 8. c. The active power output from generator in Fig. 8. d. From Fig. 8.e, the armature current of the drawn DC motor shows how the motor tracks the steam turbine. Three-phase short circuit occurs at the generator terminals for 80 ms, the fault occurs at time of 6s. In Fig. 8, despite the dynamic performances are oscillated after the fault clearance, the system stability is maintained after small time of 1.5s. The oscillations and steady-state error are minimized during this test by selecting suitable values of the PI controller in the current control loop using genetic algorithm.



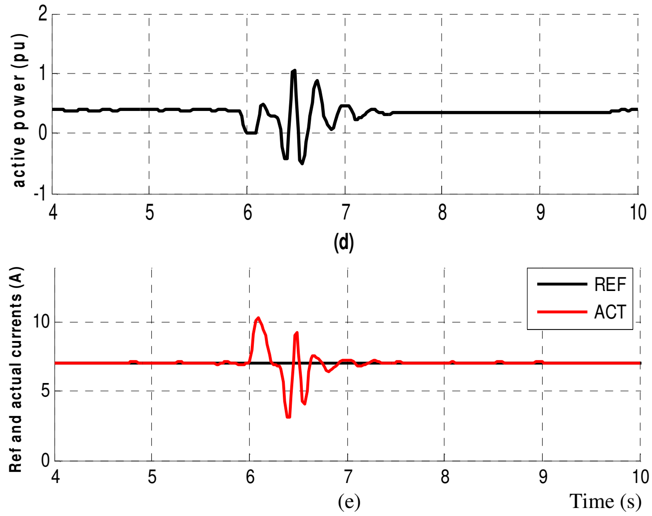
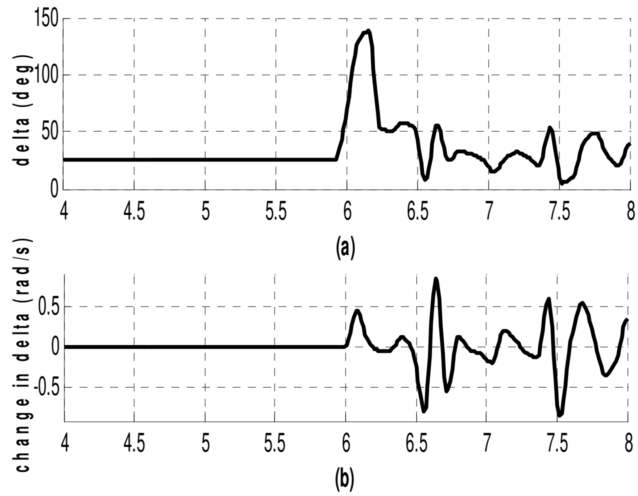


Fig. 8. Three phase short circuit for Turbogenerator system for 80 ms.

Fig. 9 is the performance of the turbogenerator system during and after three-phase short circuit at the generator terminals for long fault period of 200 ms. The constant governor valve position of 0.6 pu and an exciter voltage of 3 pu are employed to the system. The power angle delta is shown in Fig. 9. a. The rotor speed variation in Fig. 9.b, the terminal voltage of generator shown in Fig. 9. c. The active power output from generator in Fig. 9.d and the armature current of the DC motor which drawn in Fig. 9.e shows how the motor cannot track the steam turbine. Three-phase short circuit occurs at the generator terminals. The fault occurs for 200 ms and cleared. After the fault clearing, a huge and continuous oscillations occurred which led to instability and loss of synchronization. It can be concluded from Fig. 9, despite the selecting of suitable values of the PI controller using genetic algorithm, the system became unstable because of the long fault period before clearing the fault.



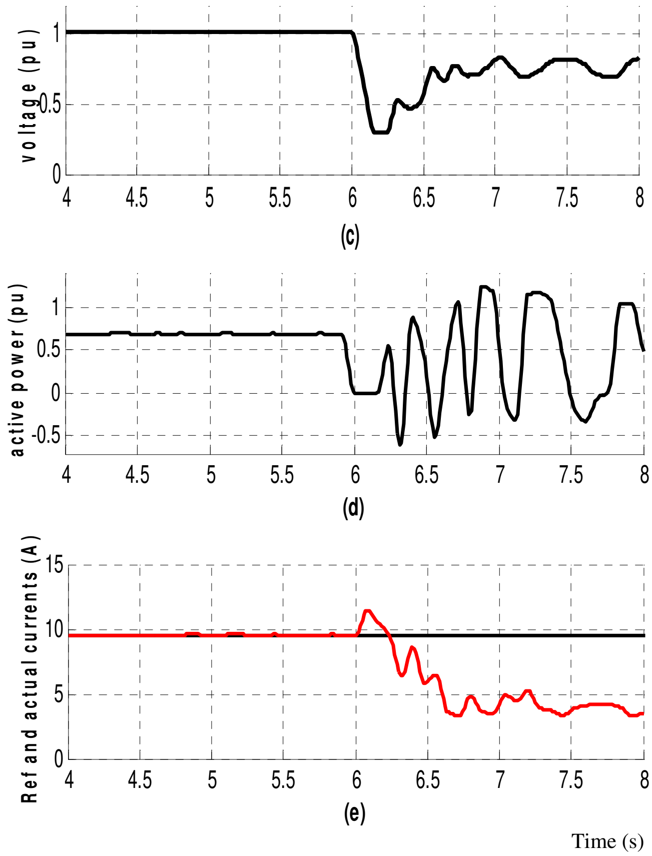


Fig. 9. Three phase short circuit for Turbogenerator system for 200ms fault period (unstable operation).

B. Validation of Wind Turbine Emulator

The proposed emulator operation is tested at the three-phase short circuit condition at the generator terminals. For this severe fault condition, the generator is directly connected to the grid through a short transmission line represented by resistance and inductance (R=0.8 Ω and L=0.08 H) respectively. The fault is applied for different time periods. Considering constant wind speed of 10 m/s during the test period as in Fig. 10. a. Fig. 10.b depicts the rotor speed and Fig. 10.c is the generator frequency, any short circuit for a small period, the speed and frequency are reduced and back to their pre-fault values. If the fault period exceeds a certain limit the system becomes unstable. For short fault period of 0.4s and 0.6s, and after the fault clearing the system returns to its steady-state condition without any severe increase in generator speed and frequency and the system is still stable. At long fault period of 0.8s, the generator speed and frequency are rapidly increased. At 33% increase in generator speed and frequency, the emulation program shut down the system before failure and all measured values fall to zero. This case is out of synchronization, disconnecting the drive system becomes a strict requirement. Fig. 10. d depicts the reference current of the emulated wind turbine dynamic equations and the corresponding actual current from the DC motor during steady-state and abnormal cases. Fig. 10.e and Fig. 10.f show the generator output power and torque, respectively. Since the wind speed is constant, the output power and torque are remaining constant at 1800 W and 11N.m respectively.

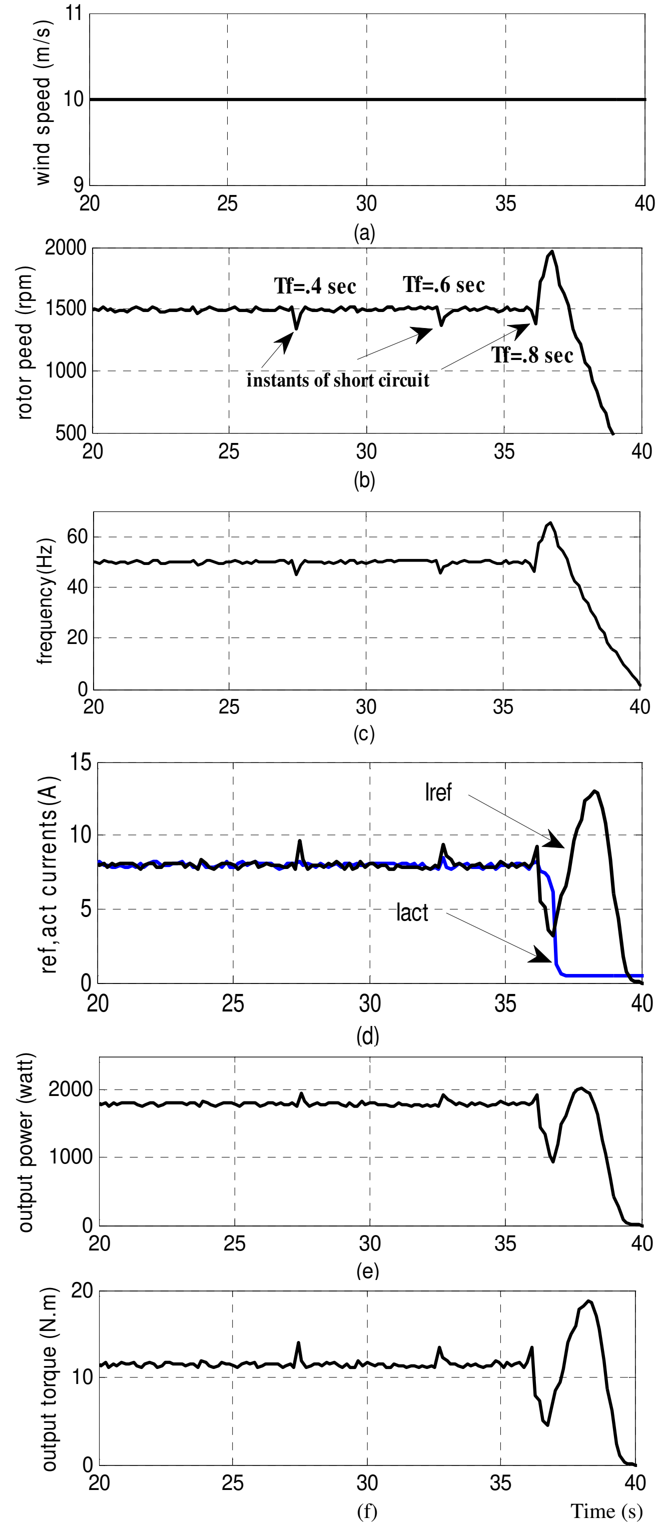


Fig. 10. Performance of the wind turbine emulator in case of three-phase short circuit at generator terminals.

VII. CONCLUSIONS AND PERSPECTIVES

In this paper, the critical energy sources represented by wind and steam turbines are emulated using 4 kW 1500 r.p.m DC motor coupled to 2kW, 380V, and 50Hz synchronous generator. The proposed unique real time affordable and scalable testbench is considered for the security and the control of both turbines besides the proactive protection and monitoring to avoid risky faults conditions. Accordingly, the security of these critical operation of energy sources can be instantaneously verified. To simulate the real steam and wind turbines characteristics, the real time LabVIEW™ control program is integrated into the experimental system together with the DC drive-controlled DC motor coupled to three-phase synchronous generator. The system is controlled through PC with interfacing cards for controlling the DC motor torque at any steam valve position and at any wind speed in case of steam and wind turbines, respectively. From the experimental results, the DC motor emulator is significantly examined for both steam and wind turbines at different normal/abnormal operating conditions. GA optimization technique, in this work, is considered for the optimal scheduling of the typical industrially favored simple PI controller. For real time emulators, the controller parameters are tuned offline around the rated operating point to provide the controller dynamic behavior with the adequate rapidity to cope with the unexpected sever fault conditions. For such a condition, the online optimization is not recommended to avoid any action delay that may damage the real system.

Under normal operation, of step changes in governor position for steam turbine and wind speed for wind turbine. Considering the three-phase short circuit at the generator terminal, which is considered among the most severe faults, the emulated systems remain stable after fault clearance but for small periods of faults. If the fault period exceeds a certain limit before its removal for both emulated turbines, the system suffers from sustained oscillations and instability risks. The proposed testbench experimental architecture can be conveniently used for adequately emulating both Steam and Wind turbines. Thanks to the LabVIEW™ software and the optimal-scheduled GA-based PI controller of the DC motor, the emulated turbines behave as their real counterparts at different operating conditions. The proper use of a unique scalable emulator for both Steam and Wind turbines is an added value for the paper. The proposed testbench and the relevant experimental system architecture without any extra devices particularly in for abnormal fault condition studies.

For the forthcoming studies, the authors will focus on defining an appropriate online approach for tuning the controller to minimize the possibility of reaching unstable operation. In addition, further studies concerning the design of intelligent controllers based on frequency feedback signal for minimizing the risks of reaching out-of-step case will be considered. The controller should automatically shut down the complete system at long periods of fault and automatically re-operate the system after fault clearing.

Compliance with ethical standards

Conflict of interest: Authors have no conflict of interest.

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee.

Human and animal rights This work does not contain any studies with human participants or animals performed by any of the authors.

Authorship contributions: All authors have been contributed in the work.

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