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Analysis of System Stability in Dual-Area Network Incorporating Renewable Energy Sources with Learning Method

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The most crucial requirement for any modern electrical system is stability. There have been recent reports of grid stability problems associated with the exponential increase in electrical and electronic loads. The test system chosen to evaluate system performance in the presence of renewable energy-based generation units is Kundur's Two-Area System. The current analysis examines problems that arise from the direct integration of these resources, including power stability at generator nodes in the grid system and rotor angle stability. This paper presents a comprehensive dynamic system optimisation technique with the aim of improving system stability in multiple ways. The study explores the effects on a two-area, four-machine system using the MATLAB/SIMULINK environment as the platform for system design and implementation. Wind energy systems are integrated first in Area 1, without the use of a dynamic optimisation control. Area 2 incorporates a dynamic optimisation controller along with solar and wind energy systems. At crucial bus points in the power system, the suggested control mechanism efficiently stabilises rotor angles and power generation.

Keywords: STATCOM, solar, wind, fuel cell, instability.

1. Introduction

Growing concerns about climate change and fossil fuel depletion are driving a shift towards sustainable energy solutions [1]. With global energy demand expected to rise 50% by 2040, industrialized nations are investing heavily in Renewable Energy Sources (RES) for energy security and environmental protection. Despite renewables providing 24% of global electricity by 2017 and nearly 30% by 2020, fossil fuels remain dominant, especially in heating and transportation . Renewable energies like solar, wind, hydro, and geothermal are vital for reducing greenhouse gas emissions. Their decreasing costs make them a key part of the energy transition. New technologies that increase fuel efficiency and lower emissions include Combined Heat and Power (CHP) systems, which use waste heat from power generation [2]. Integrating renewable energy sources like solar and wind poses significant grid stability challenges due to their variability. Unlike traditional power sources, renewables fluctuate with weather and time, necessitating costly investments in advanced grid management and energy storage technologies. Achieving high renewable penetration (30-50% of the grid) requires technological advancements to lower costs. Incorporating nuclear power as a stable, low-emission source may also be crucial for maintaining grid stability [3]. STATCOMs enhance grid stability by providing dynamic reactive power support, maintaining voltage stability, and aiding fault ride-through. They address voltage instability and rotor angle stability issues, especially in grids with high renewable penetration or weak conditions [4]. STATCOMs significantly enhance stability in renewable energy systems by addressing critical issues like rotor angle, voltage, and resonance stability. Advanced control techniques, including adaptive and coordinated approaches, optimize STATCOM performance, making them essential for integrating large-scale wind and PV systems [5].

Author(s)	Year	Reference	Method(s)	Results
Darabian, M. et al.	2020	[5]	Non-linear Generalized Predictive Control (NGPC) with internal and external control loops; simulations in MATLAB	enhanced stability in a hybrid power system using HVDC for dampening and STATCOM as a parallel compensation. Robustness assessed with several internal characteristics.
Shakerighadi, B. et al.	2023	[6]	Grid-forming (GFM) control of inverter-based generators (IBGs); simulations using PSCAD-EMT	Reviewed technical challenges and properties of different GFM methods for IBGs; simulation results for IEEE 9-bus test system.
Sinsel, S. et al.	2020	[7]	Overview of challenges and solution technologies for variable renewables	Provided an interrelation matrix of challenges and solutions; highlighted prioritization and transparency in renewable energy integration.
Kiasari, M. et al.	2024	[9]	Analysis of smart grid technologies and Machine Learning (ML) for energy management	Examined how to incorporate renewable energy sources (RES) into smart grids; highlighted developments in AMI, DCS, SCADA, and ML; highlighted the advantages of RES and the need for innovation and regulations that support it.

The work demonstrates that integrating renewable energy into the two-area, four-machine power system has a significant impact on grid dynamics, particularly under varying input conditions. The variable nature of these introduces fluctuations in power generation, leading to observable effects on rotor angular stability and reactive power balance. When further integrating solar and fuel cell systems, the combined renewable energy sources created additional challenges in maintaining system stability. However, with the implementation of an Artificial Neural Network (ANN) driving the STATCOM, the system's overall stability improved significantly. The ANN effectively optimized the reactive power support provided by the STATCOM, allowing for dynamic adjustments in response to real-time variations in grid conditions. As a result, the system exhibited enhanced voltage regulation and improved damping of oscillations, maintaining stability even under high variability in renewable energy inputs. The ANN-based controller proved to be efficient in managing the nonlinearities introduced by the renewable energy sources, ensuring smooth system operation across different scenarios.

2. MODELING TWO AREA SYSTEM

Systems comprising of multiple resources and its ability to sustain or regain synchronism after a disruption or breakdown is known as rotor angular stability. In these systems, all synchronous machines operate at a constant electrical speed of 2πf during normal operation because of the balance between the mechanical and electromagnetic forces acting on each generator's rotating masses. Because there is a consistent phase angle difference between the internal electromagnetic fields of the several machines, synchronous functioning is thus guaranteed. It is observed that, when a problem arises, an imbalance in torque causes rotor speed variations, which may result in a loss of synchronism. In this paper we have used a two-area, four-machine power system model to evaluate the grid's stability under the integration of renewable energy. For our tests, we used the Kundur two-area system as the baseline, in which we slowly integrated renewable energy sources into the system in order to assess its suitability. Three changes were made to the system: a) adding wind energy; b) integrating a hybrid system of solar and wind; and c) adding a hybrid system of solar, wind, and batteries. For each scenario, conventional generation was replaced by renewable sources to evaluate the effect on rotor angular stability.

The construction of a dynamic system optimisation controller was prompted by the results, which demonstrated notable impacts within reasonable bounds. This controller ensures strong and stable behaviour under all operating situations by using anticipatory neural network learning to forecast and stabilise system dynamics. sIn an electrical power system, a bus is typically connected to generating units that supply loads with real and reactive power concurrently, while also injecting both types of power. Bus injected power, a net power value in load flow analysis, is the result of combining the generator and load powers. The following formula can be used to calculate the net power added to a bus:

$$P_{net} = P_{gen} - P_{load}$$

The selected test system consists of two sections, each housing four machines. The extremely variable feeding wind energy resource is incorporated with the system. The system's single line diagram is shown in the figure.

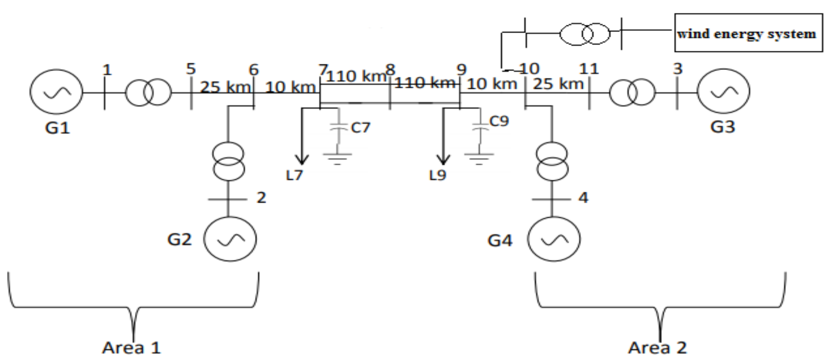

Fig. 1 Wind energy source integration with two area test model (single line diagram)

Any step-up transformer has an off-nominal ratio of 1.0 and an impedance of 0+j0.15 at 900 MVA and 20/230 kV. The nominal voltage of the gearbox system is 230 kV. Figure 1 shows the lengths of the lines. On a 100 MVA, 230 kV basis, the line's characteristics are as follows:

The intended operation of the system is for area 1 to export 400 MW to area 2. However, there are certain fluctuations at the loading sites as a result of integration with variable energy resources. Two similar places are connected by a weak tie in the system. In each location, there are two linked units with a total rating of 20 kV and 900 MVA. The generating parameters, categorised by rated MVA and kV, are as follows:

Table 2: Generator machine parameters in two area system

X_d	1.8
X_q	1.7
X_t	0.2
X'_d	0.3
X'_q	0.55
X''_d	0.25
X''_q	0.25
R_a	0.0025
T'_{d0}	8.0s
T'_{q0}	0.4s
T''_{d0}	0.03s
T''_{q0}	0.05s

3. INTEGRATION OF WIND, PV, AND FC WITH KUNDUR'S TWO AREA MACHINE MODEL

To simulate different parts of HRES, researchers have created various kinds of modelling techniques. Deterministic or probabilistic methods are used to model the performance of each individual component. This work has employed the fundamental modelling structures of the wind and solar energy systems, as well as the modelling of the PSS controllers.

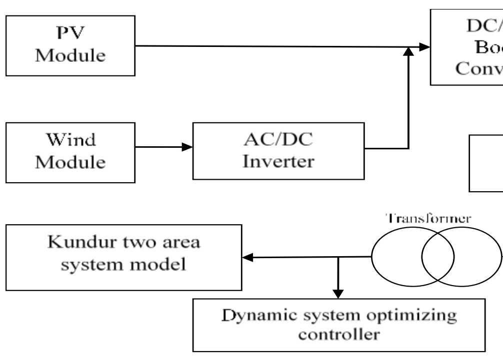

Fig. 2: Proposed Hybrid energy system topology

Environmentally friendly and abundant, photovoltaic energy produces no pollutants. The solar system's output power type is contingent upon its geographical location. One potential renewable energy source that could help people break their reliance on fossil fuels is the photovoltaic system. The possible advantages and effective usage of wind PV systems to meet consumer load requirements are investigated using battery storage and the DG supplemental unit in various hybrid PV/wind system designs.

The primary component of grid-connected solar and wind systems is the power conditioning unit (PCU), sometimes known as an inverter. It changes the direct current from the solar generator into an alternating current that satisfies the voltage and energy quality requirements of the grid. After that, the devices can consume the alternating current directly or send it to the power provider so they can get paid for their tariffs. The PCU immediately cuts off the mains supply if it is not provided. When a photovoltaic cell's voltage (V) and current (I) levels produce the maximum output power, the cell has a single operational point. These numbers translate into a specific resistance that is equivalent to V/I. Fig. 3 depicts the PV cell's designed setup.

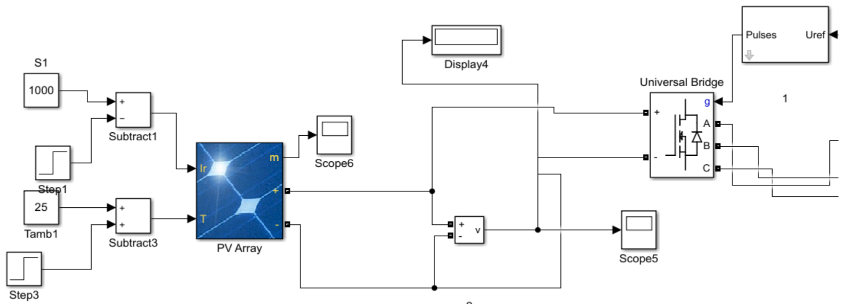

Fig. 3 Modeled solar system

An exponential diode (D), shunt resistance (Rsh), and cell photo current (I_{ph}) are linked in parallel with a series resistance (R_{sh}); the cell voltage and current are represented by Ipv and Vpv, respectively. It is able to be stated as

$$I_{pv} = I_{ph} - I_s\left(e^{q(V_{pv}+I_{pv}*R_s)/nKT} - 1\right) - (V_{pv} + I_{pv} * R_s)/R_{sh}$$
Eq (1)

Where: I_{ph}- Solar-induced current, I_S - Diode saturation current, q - Electron charge (l.6e^{-l9}C), K - Boltzmann constant (l.38e^{-23}J/K), n - Ideality factor (l~2), T - Temperature K

The sun's irradiation level and operating temperature, which are best explained as follows, are what determine the solar PV cell's solar induced current.

$$I_{ph} = I_{sc} - k_i(T_c - T_r) * \frac{I_r}{1000}$$ Eq (2)

Where:

I_{SC}Short-circuit current of cell at STC

K_i Cellshort-circuit current/ temperature coefficient (A/K)

I_r Irradiance in w/m^2 T_C ,T_r Cell working and reference temperature at STC

Photovoltaic cells have an exponential relationship between voltage and current, with the maximum power point (MPP) located at the curve's knee.

The primary energy source is the wind's interaction with the rotor blade. Turbine blades and a sizable hub make up the rotor. The blades are like the wings of an aeroplane. Usually, the blades are big. In actual operation, wind turbines with three blades are typical. The rotor's stepper drive is an extra component that aids in maintaining the rotor blades' specified operating range of 1000 to 3600 revolutions per minute (rpm). A rotor revolving around two or three propeller blades is powered by wind energy. The primary shaft, which rotates the generator to produce power, is fastened to the rotor. Consequently, the generator transforms the mechanical energy of the rotor into electrical energy.

Wind energy cannot be fully captured by the wind turbine model using PMSG wind turbines. The following formulas were used to simulate the wind turbine's component parts.

The wind turbine's aerodynamic power output is stated as:

$$P_{Turbine} = \frac{1}{2}\rho A C_p(\lambda, \beta) v^3 \qquad \text{Eq (3)}$$

where CP stands for coefficient of power conversion, v for wind speed (in m/s), ρ for air density (typically 1.225 kg/m3), and A is the sweep area (in m2) of the rotor blades.

The tip-speed ratio is defined as:

$$\lambda = \frac{\omega_m R}{v} \qquad \text{Eq (4)}$$

where R and ω_m represent the angular velocity (in rad/sec) and rotor radium (in meters), respectively.
A wind turbine's mechanical torque output (m T) is expressed as follows:

$$T_m = \frac{1}{2}\rho A C_p(\lambda, \beta) v^3 \frac{1}{\omega_m} \qquad \text{Eq (5)}$$

The power coefficient can be expressed as a nonlinear function of the blade pitch angle β (in degrees) and the tipspeed ratio (λ).

The power output is provided by

$$P_{Turbine} = \frac{1}{2}\rho A C_{p_{max}} v^3 \qquad \text{Eq (6)}$$

The power coefficient (CP) is modelled using a general equation that is based on the modelling turbine features that are discussed in [2], [7-9], and [11].

$$C_p = \frac{1}{2}\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) e^{-\left(\frac{21}{\lambda_i}\right)} \qquad \text{Eq (7)}$$

There exists a point on the wind generator power characteristic, also known as MPPT, where the output power is maximised for all wind speeds. The WECS load control causes the turbine rotor to run at a changing speed as a result, continuously drawing the most power possible from the wind.

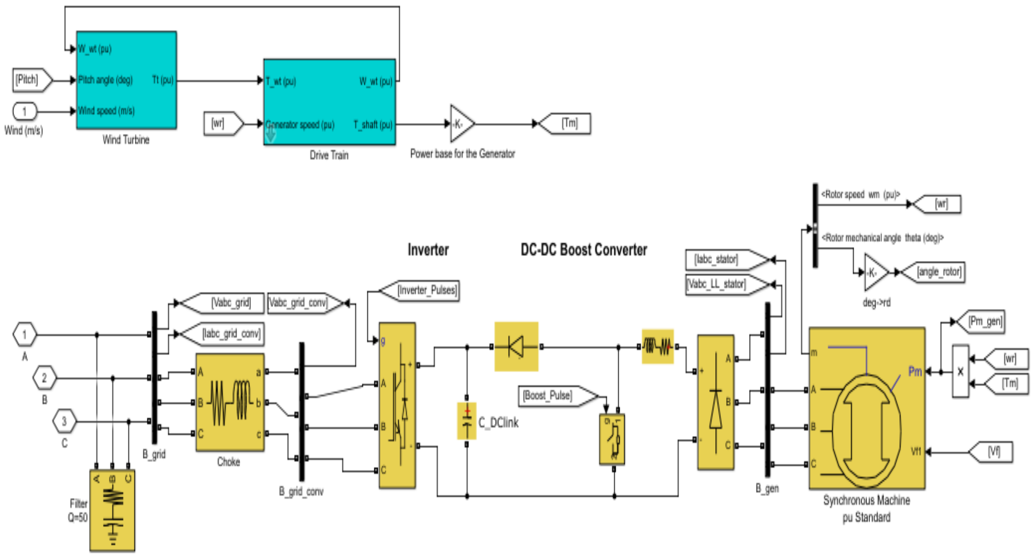

Fig. 4 Wind energy system integrated with the test system

As shown in Fig. 4, this mechanism optimises the current and voltage waveforms using the variable torque output in an effort to attain maximum output performance.

Proton exchange membrane fuel cells (PEMFCs) are electrochemical devices that convert chemical energy from a reaction between hydrogen as fuel and oxygen as an oxidant into electrical energy. A bias voltage is provided to the cell to start the electrochemical processes at the electrodes. Water splits into oxygen, protons, and electrons when it is added to the anode. At the cathode, electrons from the external circuit and protons propelled by an electric field via the PEM combine to generate hydrogen gas. Fuel cells are compact, quiet energy sources that produce electricity by burning hydrogen and oxygen. Automobile manufacturers have invested much in research and development, and the transportation sector is one of the biggest potential markets for fuel cells. Fuel cells are thought to have a more immediate market in energy production, nevertheless, because their efficiency rates—which can range from 35% to 60%—are higher than those of traditional energy generation technologies.

4. LEARNING FROM NEURAL NETWORKS (NN) FOR DYNAMICS ARRIVING AT THE INTEGRATION

An artificial neural network is one type of information processing system that can mimic human behaviour (ANN).

Even though our models could be noisy, ANNs learn from the input data and gain inherent information from the features that are taken into consideration. Information processing units are neurons, which make up ANNs. They are defined into several levels and coupled to one another by weight definitions. The interactions between every pair of neurons are shown by synaptic weights. Information is dispersed throughout the neurones by these structures. The mappings between inputs and anticipated output reactions are made by combining transfer functions. An algorithm for artificial neural network learning can be evaluated using the self-adaptive information model recognition approach.

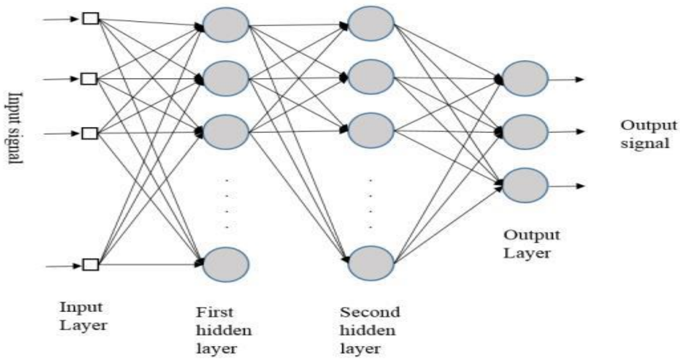

Fig. 5 Hidden Layers in the neural network learning model

As illustrated in Fig. 5, neural networks can be classified as either single-layer perception (SLP) networks or multilayer perception (MLP) networks. Multiple layers of straightforward, two-state sigmoid transfer functions with processing neurones interacting through weighted connections make up the multilayer perception network. The three layers of a conventional feed-forward multilayer sensory neural network are input, output, and hidden. Since multilayer perception (MLP) is a general function approximation and has been employed in numerous previous ANN investigations, this work employs it in conjunction with the back propagation learning technique.

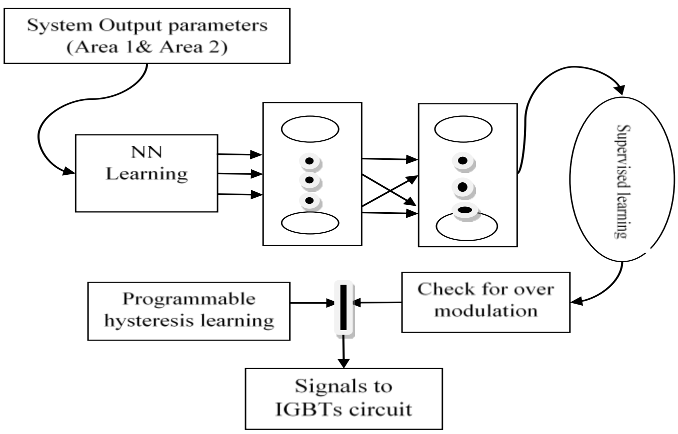

Fig. 6 NN controller Technique for driving IGBTs of STATCOM

ANN models were developed using an investigation of the relationship between input and output variables. As illustrated in Fig., the three primary layers comprising the neural architecture were the input layer, the output layer, and the hidden layer. This network's objective was stated as follows:

$Y_j = f(\sum w_{ij} X_{ij})$ Eq(8)

Yj is the output of node j, while f (.) is the transfer function. With wij representing the connection weight between nodes j and i in the bottom layer, the input signal from node i to node j is represented as Xij. Using an IGBT based automatic bridge circuit switching mechanism with a suitable controlling optimising algorithm, the controller was created to achieve machine stability at the grid. System electrical output characteristics are studied in conjunction with system oscillations and a neural network is trained to learn the system as much as possible from it. In order to balance out the disruptions caused by the changes resulting from the integration of renewable energy resources, signals are generated to an IGBT-based bridge circuit. Figure 6 shows the flow chart of the system control that was used to create the suggested system dynamics controller. Variable activation functions of the hidden units are made possible by the gradual addition of new hidden units. For networks with binary outputs, sigmoidal triggering functions work best, but this isn't always the case for outputs that are constantly weighted. Less computation and hidden unit requirements can result in faster learning and smoother approximations when additional hidden units with distinct activation functions are permitted.

5. RESULTS

For analyzing the performance some built-in functions for creating graphs are utilized, along with measurement toolboxes included in MATLAB. In order to reduce reliance on fossil fuels, hybrid energy systems can be connected to micro-grids and larger grids, as well as fuel cells, solar, and wind power to generate electricity for local use. This is because the world is moving towards a better future where a larger share of the dispersed generation exists when compared with current centralised generation. The primary goal of the endeavour has been to stabilise grid parameters in order to integrate various energy sources at various places. In order to achieve this, a two-area test system has been set up, and the effectiveness of the recommended controller design is assessed by an analysis of the scenarios listed below.

Case 1: Two-area system sans STATCOM controller that integrates with wind

Case 2: Dynamic system optimising control and integration of renewable energy sources in a two-area system to improve system stability

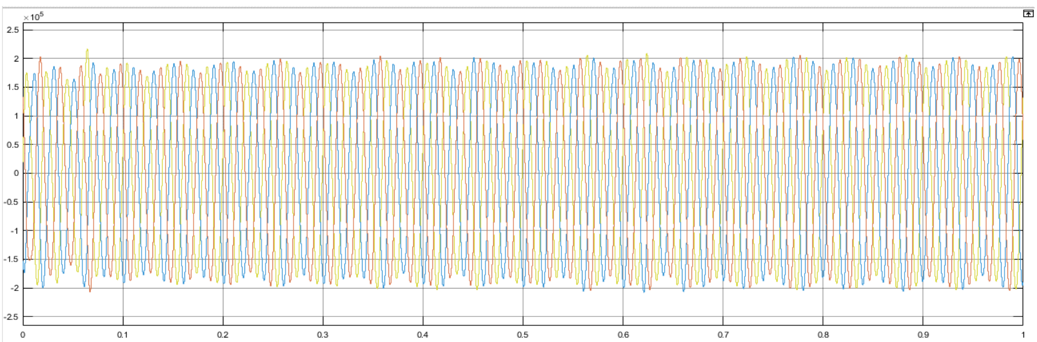

Fig. 7 Three Phase voltage in the system for case 1

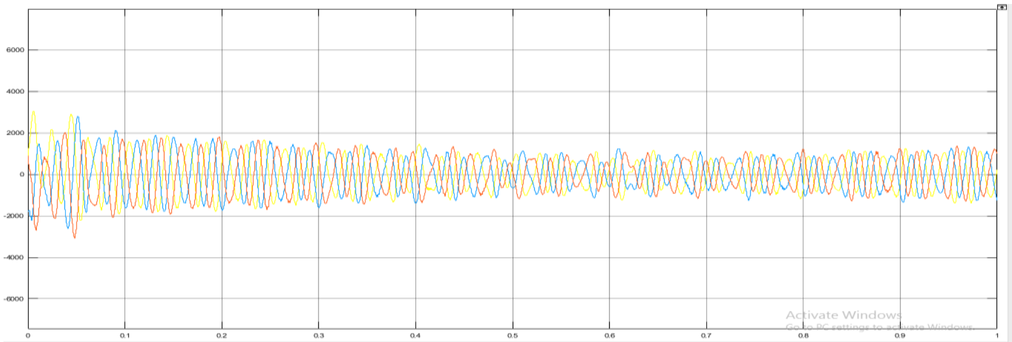

Fig. 8 Current in the system for case 1

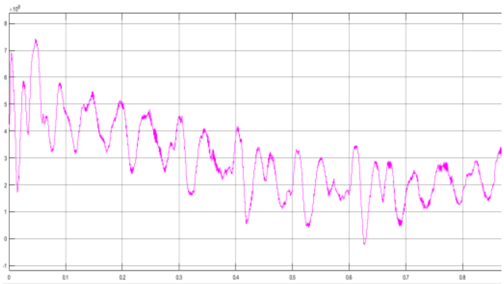

Fig. 9 Case 1 system active power output

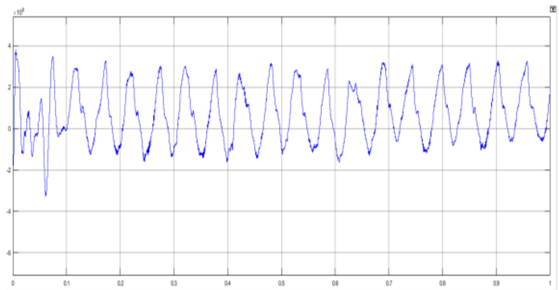

Fig. 10 Case 1 system active power output

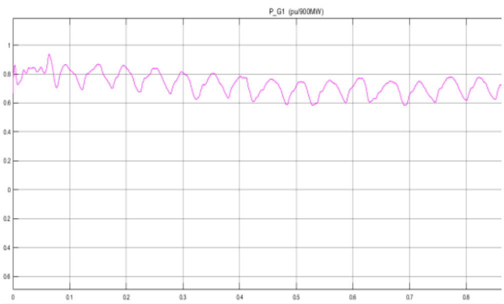

Fig. 11 Case 1 generating terminal Power stability (p.u) of the machines

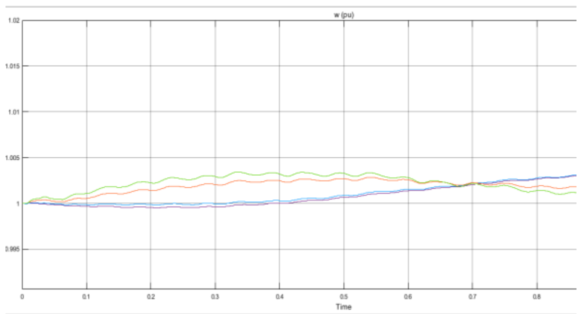

Fig. 12 Case 1 rotor speed analysis in the system

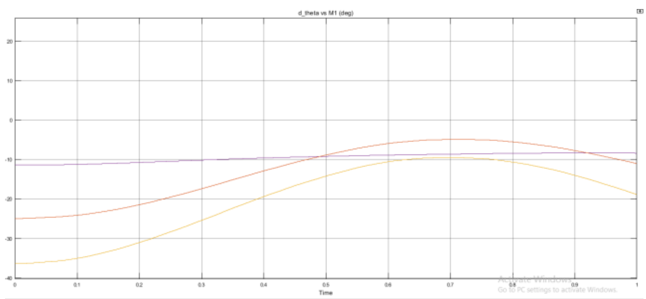

Fig. 13 Case 1 Rotor Angle Deviation analysis in the system

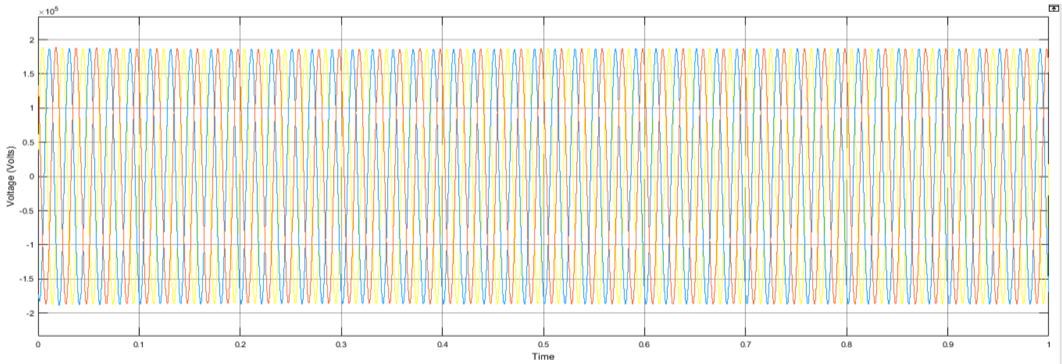

Fig. 14 Three Phase voltage in the system for case 2 with proposed ANN based controller

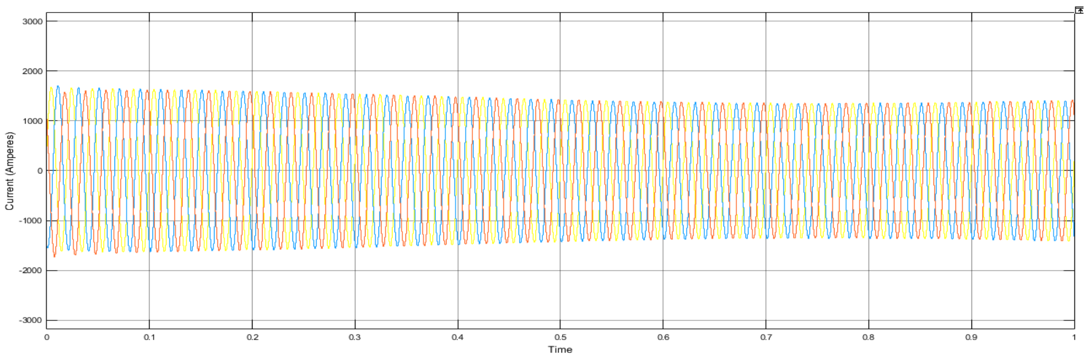

Fig. 15 Current in the system for case 2 with proposed ANN based controller

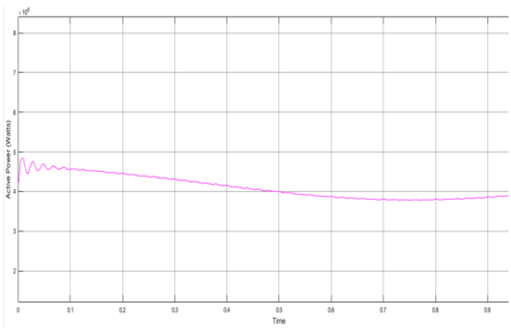

Fig. 16 Case 2 system active power output

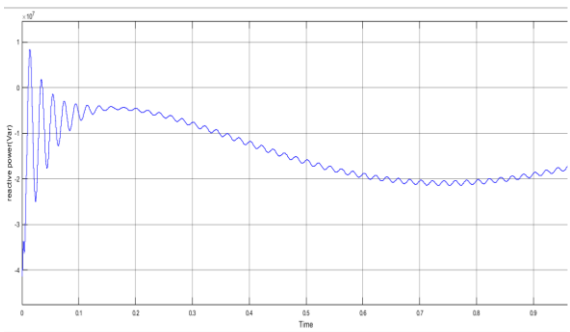

Fig. 17 Case 2 system reactive power output

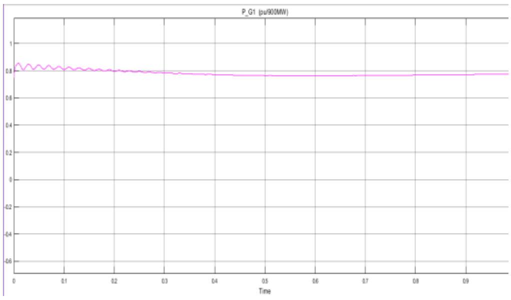

Fig. 18 Case 2 generating terminal Power stability (p.u) of the machines

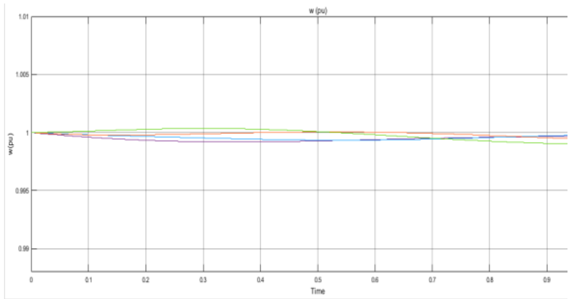

Fig. 19 Case 2 rotor speed analysis in the system

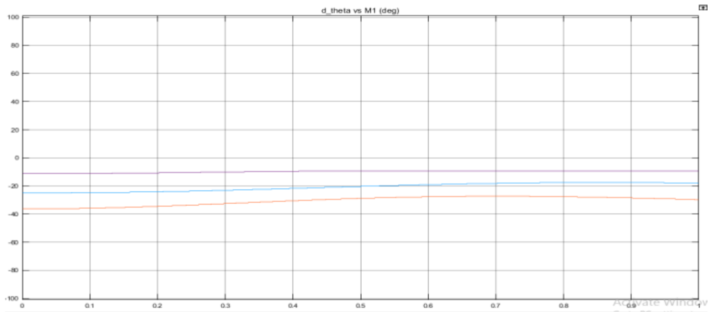

Fig. 20 Case 2 Rotor Angle Deviation analysis in the system

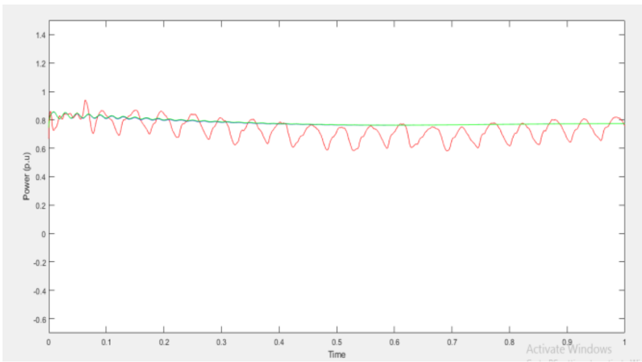

Fig. 21 p.u. graphs showing comparative power stability at the generating terminal

Fig. 21 shows the power stability that was noted in the test system at the power system's producing bus in the P.U. After integrating renewable energy sources, the system shown in the red graph experiences unstable power at the bus due to a lack of optimisation control that powers the STATCOM. The impact results from renewable resources' inconsistent power feeding quality in response to changing environmental circumstances.

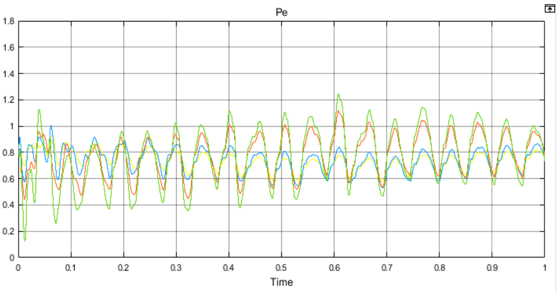

Fig. 22 Machines with electrical power Pe (p.u.) in case 1.

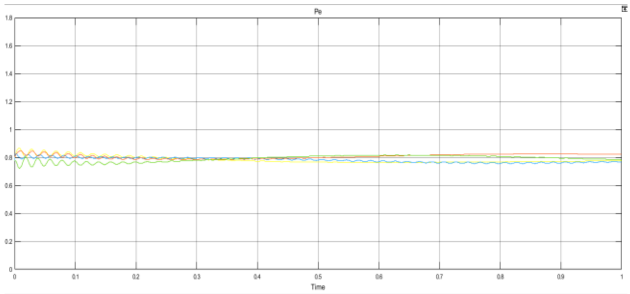

Fig. 23 Stability of electrical power [Pe (p.u)] in devices in case 2.

The graphs display the electrical power Pe of the devices in the two area systems when they are integrated with renewable energy sources. The graphs for cases two and three demonstrate the machines' more consistent power when the suggested STATCOM with ANN control optimisation is integrated. Many aspects of the two area system's grid dynamics optimisation control's effectiveness have been investigated. Upon comparing the two cases' producing terminal power stability, individual machine electrical power, and rotor angle stability, it is discovered that, in the absence of optimisation control, the system in case 2 performs better than the one in case 1.

6. Conclusion

Numerous technical issues affect grid-connected systems, including issues with power quality, fluctuations in voltage and power, storage issues, protection issues, islanding, etc. Variations in frequency and voltage are problems with power quality. The Kundur Two Area System has been selected as a test system in order to evaluate system performance in the presence of producing units based on renewable energy. At the machine's generating locations, the direct integration of these resources was checked for a number of instability issues, such as power stability and rotor angle stability. A universal dynamic system optimising control using the ANN learning method has been presented in this work to improve system stability in all aspects. The basis for creating and implementing the system is the MATLAB/SIMULINK environment. By integrating a wind energy system in area 1 without a dynamic optimisation controller and then building systems with both solar and wind energy in area 2, with a dynamic optimisation controller, the effects on the two area four machines system have been studied. To maximise the output from the dynamics controller, the system settings are modified through the use of a forward learning technique based on neural networks. The system yielded the following noteworthy outcomes.

- Compared to the system with dynamic system optimising control using NN learning, the electrical power Pe for the machines in the controller-less system was noticeably more erratic and unstable.

• At the generating bus point, the recommended power system management also stabilised the power and rotor angle stability.

The suggested NN learning based control of the dynamic system optimising control for system stability enhancement may be a preferable alternative for integrating any kind of renewable energy resource-based producing system with the grid since it can alleviate the majority of the quality issues originating from it.

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