Bulletin of Electrical Engineering and Informatics
Vol. 11, No. 2, April 2022, pp. 589~601
ISSN: 2302-9285, DOI: 10.11591/eei.v11i2.2730

Performance improvement of stand-alone induction generator using distribution SSC for wind power application

Mahmood T. Alkhayyat[1], Ziad Saeed Mohammed[2], Ahmed J. Ali[1]
[1]Department of Electrical Power Technology Engineering, Technical Engineering College/Mosul, Northern Technical University, Mosul, Iraq
[2]Department of Computer Technology Engineering, Technical Engineering College/Mosul, Northern Technical University, Mosul, Iraq

Article Info

Article history:

Received Oct 23, 2020
Revised Dec 27, 2021
Accepted Feb 16, 2022

Keywords:

DSSC
FACTS
SEIG
Stand alone
Wind energy

ABSTRACT

Self-excited induction generators (SEIGs) are used in wind turbine system because of high reliability, rigidity, simple structure, and capability to work under severe badly operating conditions. This type of generator has a poor terminal voltage and frequency regulation during changing the connected loads due to the absence of constant excitation current. Therefore, it is essential to stabilize the generated voltage and frequency besides suppress the injected harmonic current components. In this work, the dynamic performance of SEIG with distribution static series compensator (DSSC) is analyzed. The DSSC based on neuro-fuzzy controlled (NFC) is applied to control both voltage and frequency to enhance the regulation of SEIG. The NFC is used to control the DSSC which leads to balance the requirement of the reactive and active power of stand-alone grid under load variation and attempts to obtain a constant terminal voltage. The model is simulated using MATLAB/Simulink. The NFC structure designed to regulate and control the output voltage of the SEIG driven by a wind turbine to feed a consumer in remote and rural places. Furthermore, the power system parameters calculated depending on the d-q theory. Modeling results explained that the suggested controller is consistent and tough related to the conventional types.

Corresponding Author:

Mahmood T. Alkayyat
Department of Technical Power Engineering, Northern Technical University
AlMinsaa St, Mosul City, Nineveh Governorate, Iraq
Email: m.t.alkhayyat@ntu.edu.iq

1. INTRODUCTION

Series capacitors are usually used as a compensator in AC line to reduce voltage drop, increase power transfer capacity, and improve transient stability. The fixed capacitors are an efficient and cost-effective slow compensation way for a certain situation and limited compensation capability. In other hand, low frequency resonance may occur with the line inductive reactance. Flexible AC transmission system FACTS controller has prepared as an electric system to manage with the stated problems [1]. System terminal voltage, line impedance, and load angle can be controlled to improve the system steady-state and transient performances [2]. FACTS devices offer fast and highly effective flexible series compensation to control power flow and enhance the lines stability. Any possibility for low frequency resonance can be avoided easily by an adaptive controller. The distribution static series compensator (DSSC) can provide critical line impedance compensation by inserting voltage in series with the line impedance that has a manageable magnitude and phase angle [3]. Self-excited induction generator is one of the most appropriate stand-alone mode generators (SEIG). SEIG has a wide attraction in many functions due to its characteristics of robustness, reliability, low losses, and high efficiency, and relatively low cost. These types of generators are used in large ships and to supply electric power to farm fields. It is also used in supplying customers who live in rural societies and remote places. The supply of electrical power through the convention grid is useless and needs very high costs. This type of induction generators is usually driven by a wind energy system with a bank of capacitors that connected on the terminals of the stator [4]-[7]. The shunt capacitors are used to supply the generator with the primary excitation current for the no-voltage build-up. When the SEIG works, the excitation current is fed through the stator currents. There are several ways to connect the capacitors on the generator such as shunt, long shunt, and short shunt. In this work, along the shunt method or the so-called series connection has been applied. Unfortunately, these types of generators are affected by the sudden change of loads that impact on both frequency and generated terminal voltage. Based on these issues, voltage and frequency regulation is weak and unacceptable. These drawbacks can be solved using several topologies specially FACTS family to the ends of the self-exciting induction generator [8].

DSSC has been used to compensate the effect loading currents coupled through the stator terminals of three-phase SEIG. SEIG can be safe feeds the applied three-phase loads at rated power. When the applied load changed according to increase demand or due to any abnormal operation leads to a shortage on reactive power. Adding DSSC has been used to adjust the SEIG's terminal voltage by supplying the required reactive compensation power and suppress the inserted components of harmonics due to loads at the same time. The performance operation of the induction generator–compensator system is tested under both balanced and unbalanced loads. Also, the dynamic performance of the SEIG for different loads has been considering to examine the voltage regulation. Therefore, different methods have been applied to obtain a constant voltage on the terminals of SEIG. These approaches include an arrangement of a constant capacitor and thyristor-controlled device which is called the static var compensator, it is used to improve the voltage regulation of the generator, it produces a low order of harmonics due to line current switching and heavyweights and large size of capacitors [9]. Due to fast improvements on the switching process of power electronic devices, indirect vector control (IVC) is investigated. Two convertors with neural network controller NNC are used to improve the performance of SEIG [10]. Novel artificial intelligence methods for designing a FACTS-based controller, such as particle swarm optimization [11], differential evolution [12], neuro fuzzy [13]-[14], and genetic algorithm [15], have been proposed in recent years. The artificial neural network (ANN) method has been used in a variety of power engineering applications since 1988, including economical load dispatching, power system stabilizers, and so on. These applications have proved that ANN controllers improve power system in the online and offline applications [16]. For parallel FACTS devices, the ANN with fuzzy logic controller neuro fuzzy controller is useful. The goal of this research is to develop a DSSC that controls power flow and voltages in a transmission line using a neuro-fuzzy controller NFC.

2. MATHEMATICAL MODEL OF SEIG

Explaining the dynamic model of SEIG in stationary reference frame theory (dq axis) is given below depending on the Figures 1(a) and (b) [17]:

$$[V] = [R][i] + [L]\frac{d}{dt}[i] + w_r[G][i] \tag{1}$$

Then based on (1), the derivative currents matrix can be written by:

$$\frac{d}{dt}[i] = [L]^{-1}\{[V] - [R][i] - w_r[G][i] \tag{2}$$

Where G, L, R, I, and V are rotational inductance matrices, inductance, resistance, current and voltage which are given by:

$$[V] = \left[v_{ds}\ v_{qs}\ v_{dr}\ v_{qr}\right]^T,\ [i] = \left[i_{ds}\ i_{qs} i_{dr}\ i_{qr}\right]^T,\ [R] = \mathrm{Diag}[R_s \quad R_s \quad R_r\ R_r]$$

$$[L] = \begin{bmatrix} L_{ls+}L_m & 0 & L_m & 0 \\ 0 & L_{ls+}L_m & 0 & L_m \\ L_m & 0 & L_{ls+}L_m & 0 \\ 0 & L_m & 0 & L_{ls+}L_m \end{bmatrix},\ [G] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -L_m & 0 & L_{ls+}L_m \\ L_m & 0 & L_{ls+}L_m & 0 \end{bmatrix}$$

The developed electromagnetic torque of the induction generator is computed based on the following formula:

$$T_e = \frac{3}{2}\frac{P}{2}L_m(i_{qs}i_{dr} - i_{qr}i_{ds}) \tag{3}$$

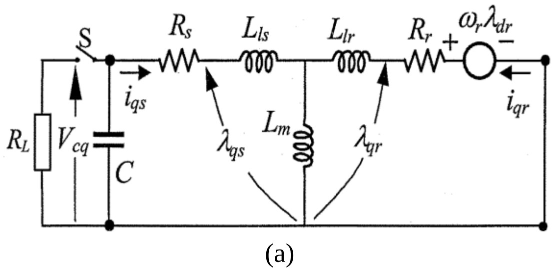


Figure 1. The dq model of the SEIG (a) d-axis and (b) q-axis

3. DSSC MODEL AND CONTROL

The DSSC injects a voltage with a nearly sinusoidal variable amplitude. A VSC powered by a DC power source serves as the DSSC's soul. Figure 2 depicts the essential structure of the DSSC with SEIG. Without an external DC link, the inserted voltage is columnar with the line current and follows a capacitive or inductive reactance in series with the transmission line. In addition, a small portion of the inserted voltage is in phase with the line current to compensate for inverter losses. If the inserted voltage causes the line current that produces the line current to increase in addition to the power flow through the AC line, it will compete with a capacitive reactance in series with the AC line. When a lagging line current in relation to the intended voltage competes with an inductive reactance connected in series with the AC line, the system reduces the line current and power flow through the line. The controller has the ability to rapidly change the level and phase of the compensating voltage. The inserted voltage is determined by the transmitted load voltage V and active power P. As a result, by inverting the polarity of the inserted alternating current voltage, the transmitted power can increase or decrease. If the reactive line impedance is increased, the inversed voltage will add directly to the line's reactive voltage drop. Furthermore, if the inserted voltage exceeds the voltage impressed through the uncompensated line (|Vcompensation|>|Vsource-Vload|), the power flow can be reversed. The system's operation stability can be detected using both +ve and -ve power flow. The DSSC has a fast sub-cycle response time and a smooth and continuous transition from positive to negative power flow via zero voltage injection [18].

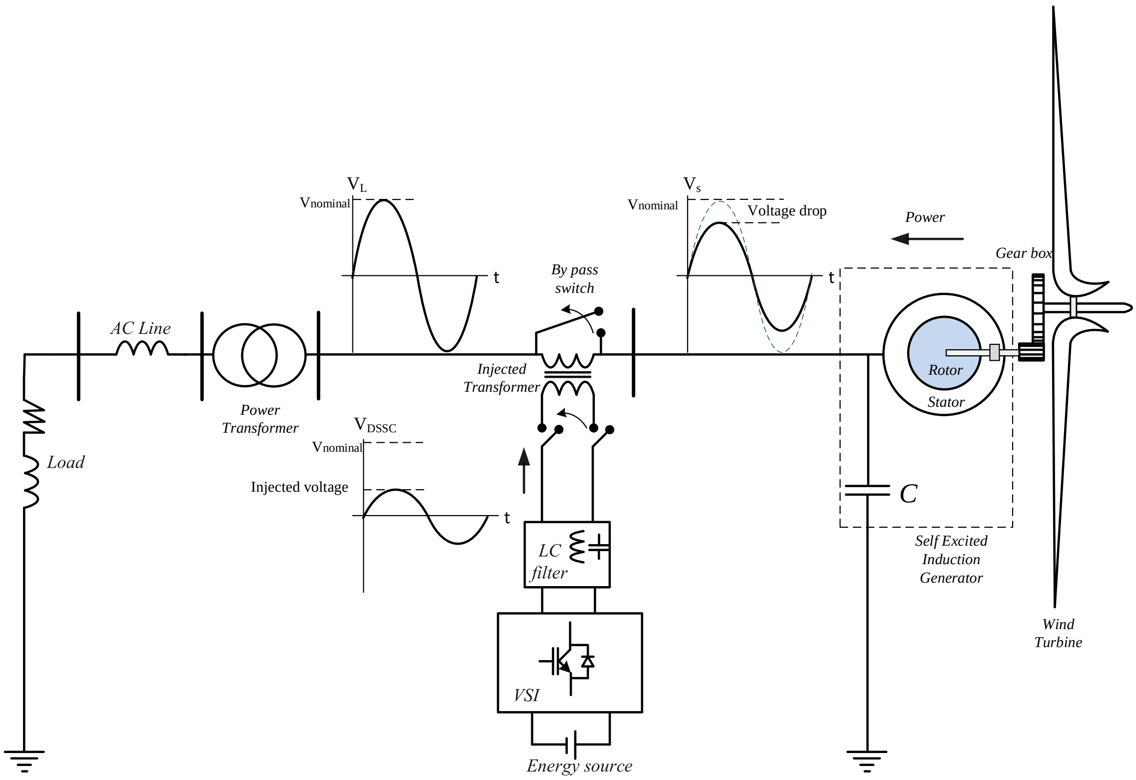


Figure 2. Essential structure of SEIG with DSSC

4. MEASURING LOAD VOLTAGE

The dq concept, which is suitable for transient or steady state operation, is used to measure active power and load voltage. It is also applicable to common current and voltage waveforms. Another important feature is the design ease, which includes an algebraic design concession to the need to break away the mean and alternated magnitudes of the designed power factor. Dq method converts a stationary coordinate system abc to dq rotating coordinates, a process known as "park transformation" [19]. The change in time-domain voltages in the natural frame (Va, Vb, and Vc) can be explained as:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\emptyset) & \cos(\emptyset - \frac{2\pi}{3}) & \cos(\emptyset + \frac{2\pi}{3}) \\ -\sin(\emptyset) & -\sin(\emptyset - \frac{2\pi}{3}) & -\sin(\emptyset + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\emptyset) & \cos(\emptyset - \frac{2\pi}{3}) & \cos(\emptyset + \frac{2\pi}{3}) \\ -\sin(\emptyset) & -\sin(\emptyset - \frac{2\pi}{3}) & -\sin(\emptyset + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (5)$$

$$\emptyset = (\omega t + \theta) \quad (6)$$

Where Ø represents the angle between the rotating and fixed coordinate systems, θ denotes as the phase shift of the injected voltage. From in (4) and (5), the load voltage compensated and active power values are calculated by:

$$p = V_d I_d + V_q I_q \quad (7)$$

$$V = \sqrt{V_d{}^2 + V_q{}^2} \quad (8)$$

Figure 3 depicts the DSSC control system. The load voltage *V* is designed based on (8) it operates as the feedback closed loop control signal. The desired V_{ref} is matched with the *V* to generate error signals $Erorr_v$ as:

$$Erorr_V = V_{ref} - V \quad (9)$$

The inserted voltage's phase angle can be tuned to create compensation in phase or anti-phase with the reference.

$$\delta = \emptyset \pm \gamma \quad (10)$$

Where γ can be attuned based on the Error sign in (9).

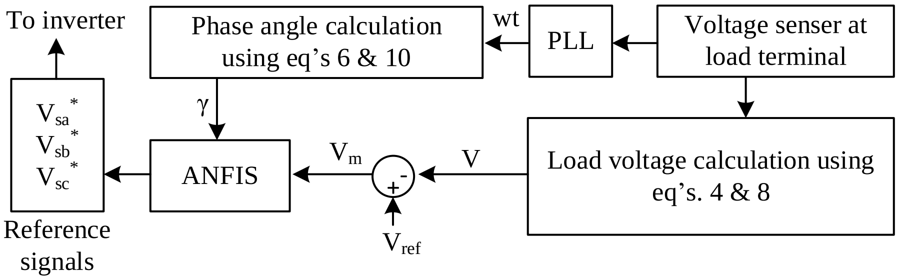


Figure 3. DSSC control system

5. SYSTEM CONTROL DESIGN

Fuzzy logic controllers FLCs are appropriate for undefined or rough reasoning, specifically for complex system that includes mathematical model. Takagi-sugeno TS was chosen for this study because an

FLC system has many fuzzy inference mechanisms. The ANN has been trained to tune and select the membership functions MF of the TS-FLC, similar to a PI controller. TS-FLC has nonlinear elements of the gain controller which highly deviats the rang of the controller gain. Random parameters are selected which may possibly guide to a sufficient response of the system or instability [20]. The best system response can be obtained by using NFC to adjust the FLC parameters and rules via the ANN learning algorithm. [21]. During the training stage, the input and output MSFs are chosen. Designed FLC system has seven layers; during training, the parameters of each node at each layer must be tuned. [22] specifies and describes the output of these layers that correspond to FLC design steps. The goal of learning algorithm is to modify the input and output MF so that NFC output matches training data. A hybrid learning strategy (gradient descent-GD and lease squares estimate-LSE) is used to classify network parameters [23]-[25]. The input universe of discourse is divided into nine triangular MF that overlap by 50% in this study. As a result, 81-control rule and linear functions want to determine for two inputs. To tune TS rules using NFC, two groups of data are generated. Input data consists of an Errorp, Errorv, and m modulation index vector. The proposed NFC takes slightly less time to calculate than Mamdani type of classical FLC. The designated system is made up of a single machine with an infinite bus bar.

6. STUDY OF SIMULATION

The MATLAB program is used to model the SEIG-designed power system with DSSC controller. The model depicted in Figure 4 is intended to investigate the performance of the proposed control system when the inductive load state changes step by step. The compensation system provides a DC voltage source to feed or absorb the system's active and reactive power. The load voltage changes in two steps at times equal to one and two seconds, respectively, and the parameters (load voltage, rms of load voltage, load current, electromagnetic torque, rotor current, active and reactive power) are shown in Figures 5-12 without DSSC. After adding the DSSC by injected controlled voltage, the performance of SEIG enhanced as shown from the parameters in Figures 13-20. Figure 21 shows the injected voltage and load voltage, as the load voltage drop happened due to the increasing of load at t=1, DSSC injects the compensated voltage and keep the load voltage within a nominal value. Figure 22 illustrates total harmonic distortion THD of the load voltage during DSSC action. Simulation results demonstrate the effectiveness of the DSSC to compensate the load voltage and enhanced the performance of the SEIG in other parameters. Also, the results evidence the positive effect of the NFC for controlling DSSC. Furthermore, these results manifestates that the suggested controller can develop the voltage shape of SEIG and the system becomes robust against load variation.

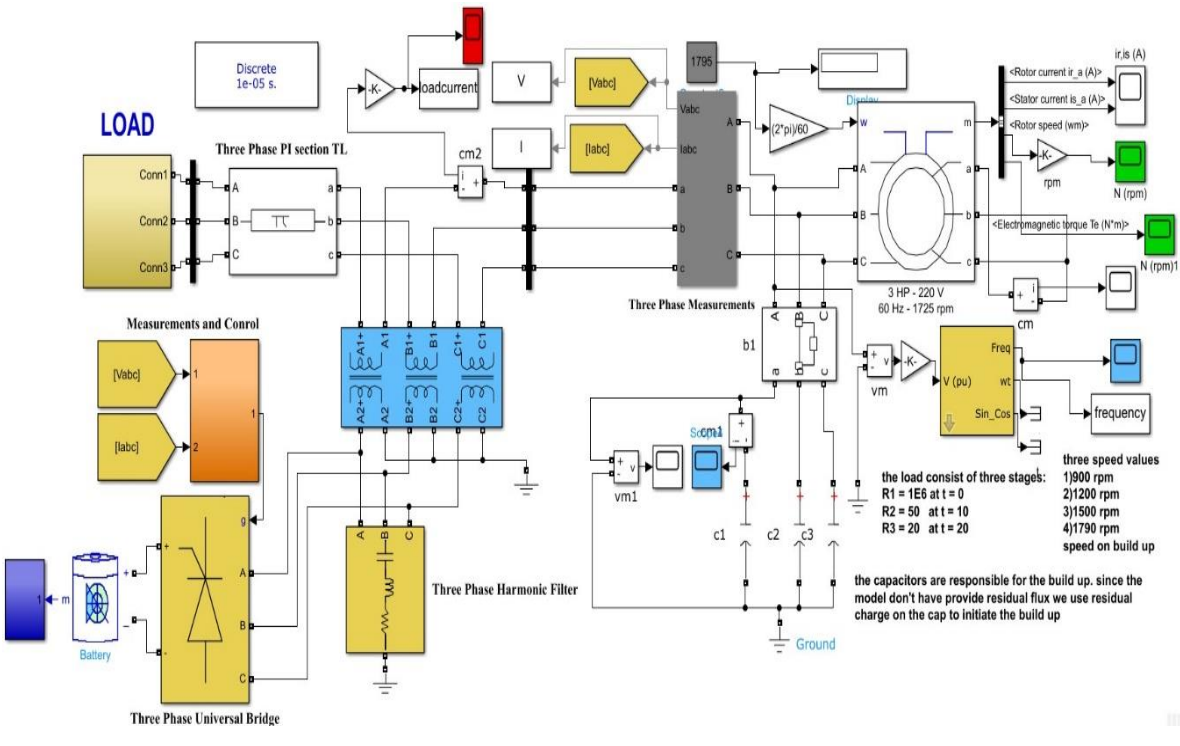


Figure 4. MATLAB simulation of the system model

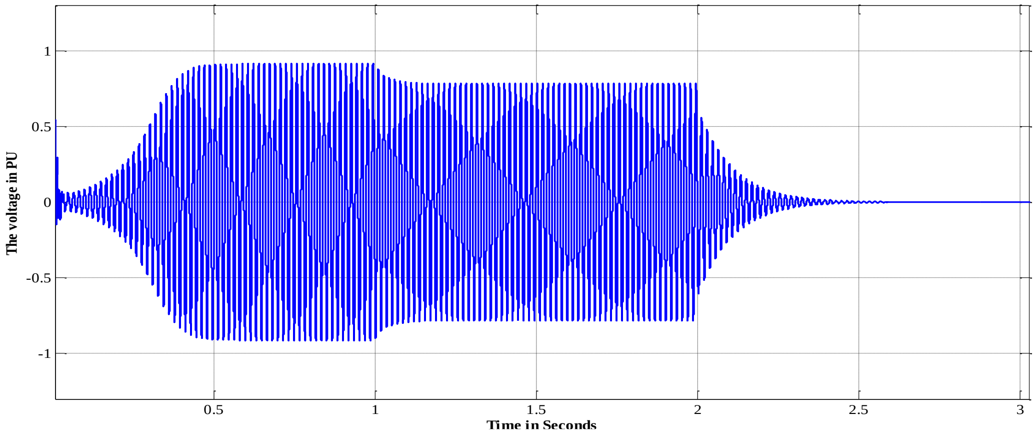


Figure 5. Load voltage without DSSC

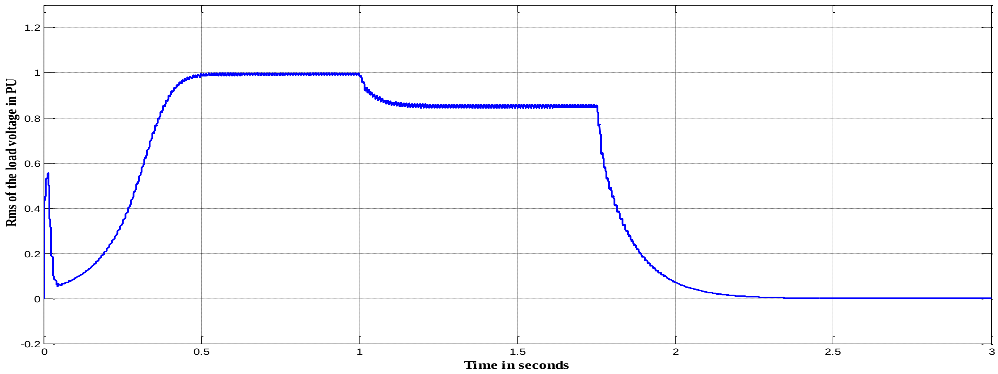


Figure 6. RMS load voltage without DSSC

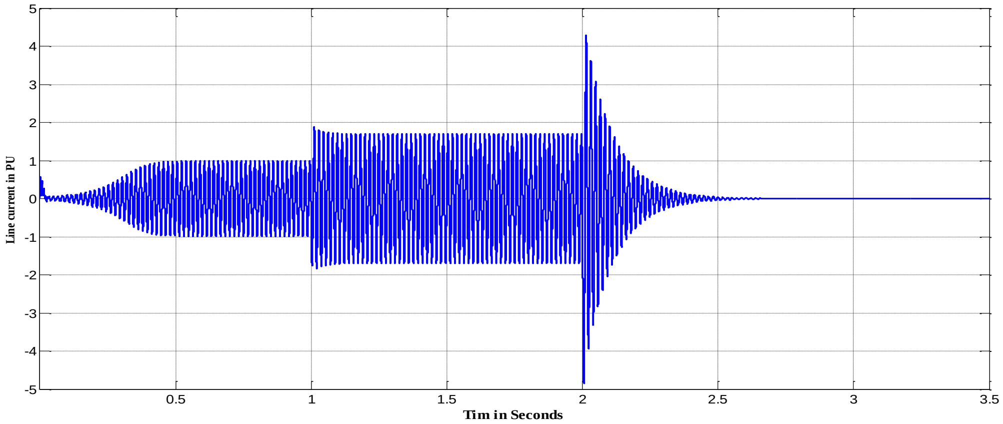


Figure 7. Line current during load variation

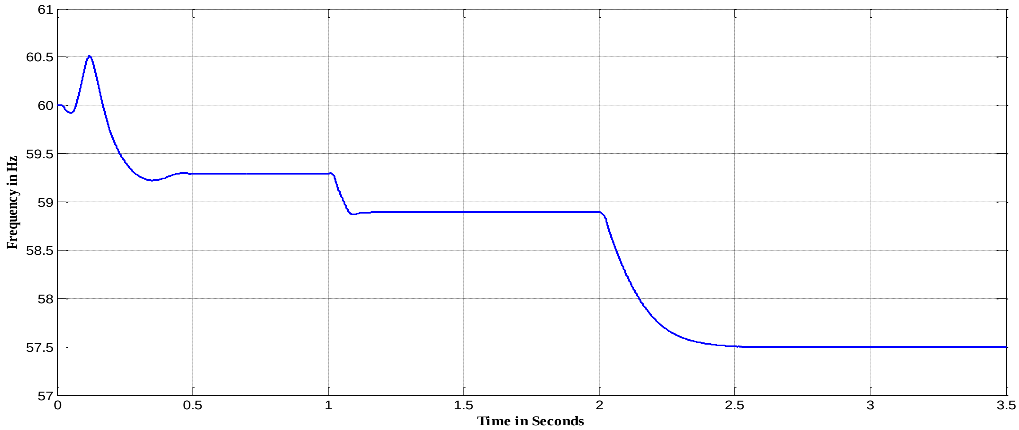


Figure 8. Line frequency during load variation

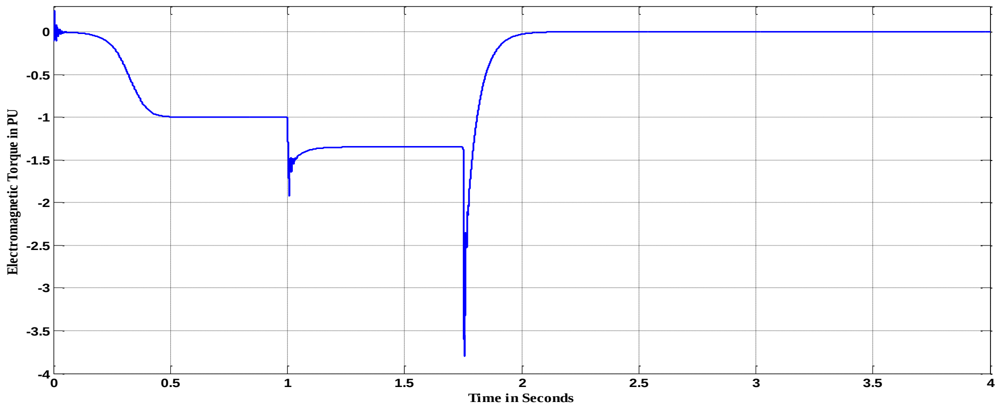


Figure 9. Electromagnetic torque during load variation

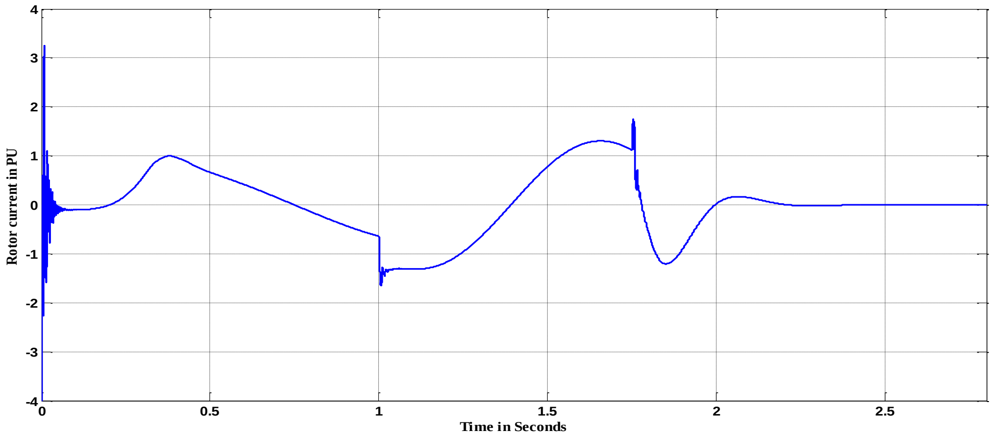


Figure 10. Rotor current during load variation

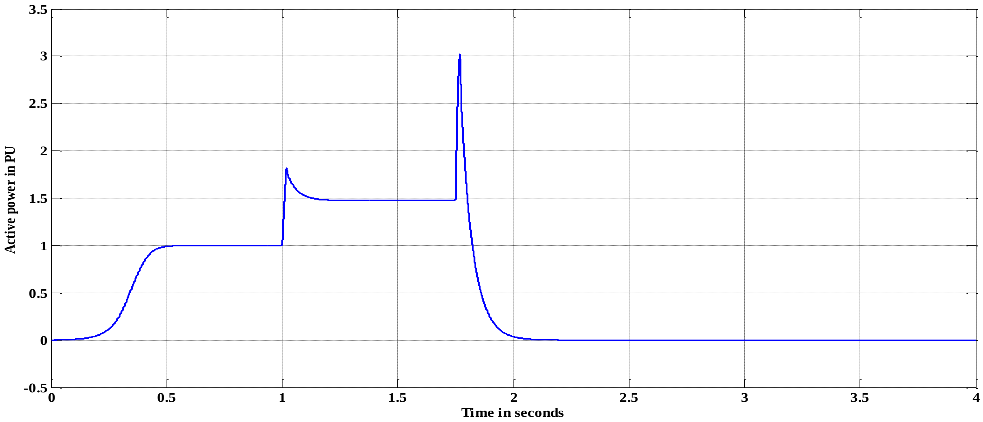


Figure 11. Active power output during load variation

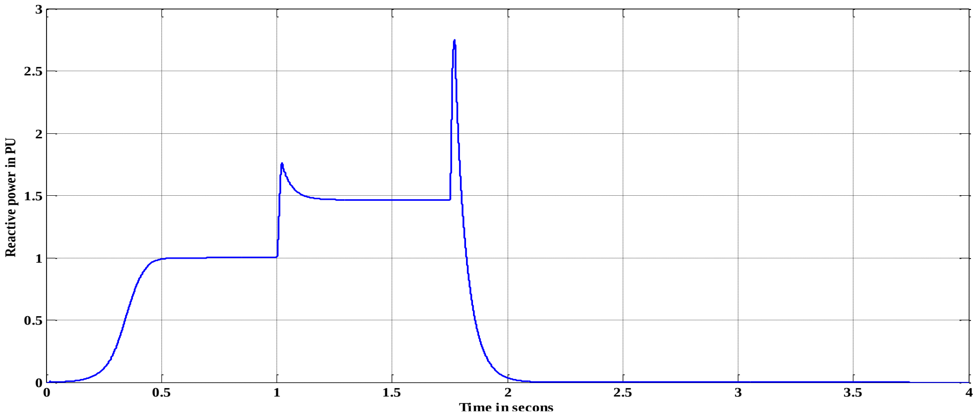


Figure 12. Reactive power output during load variation

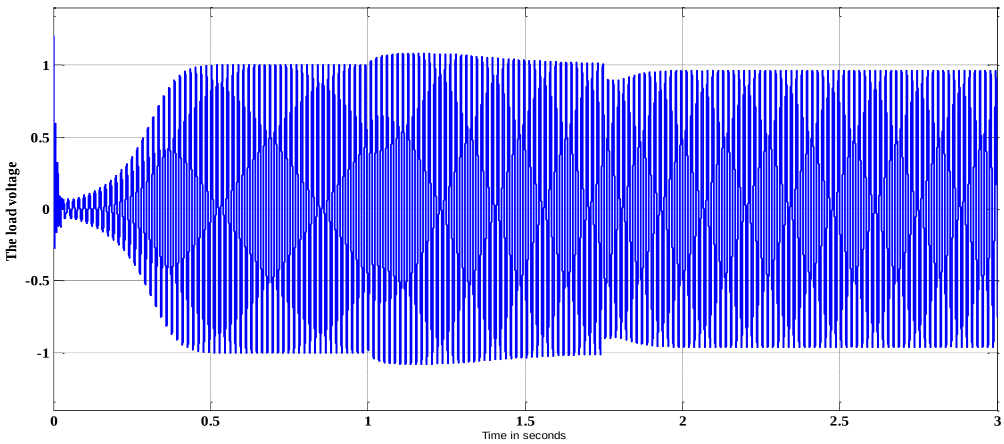


Figure 13. Load voltage with DSSC

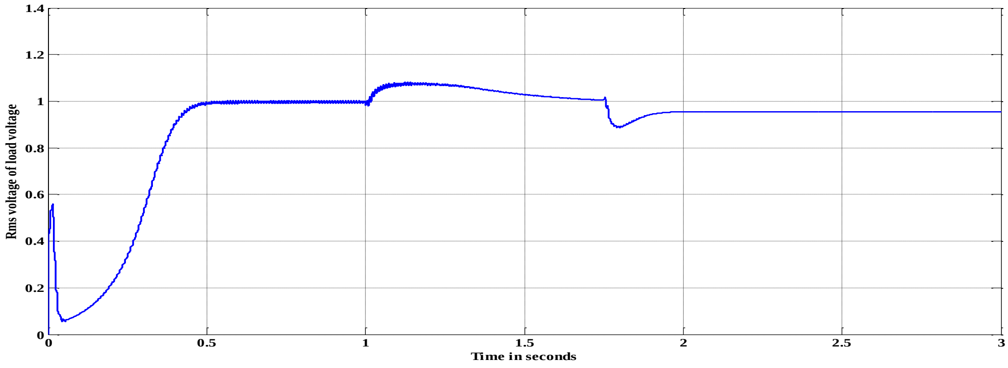


Figure 14. RMS load voltage with DSSC

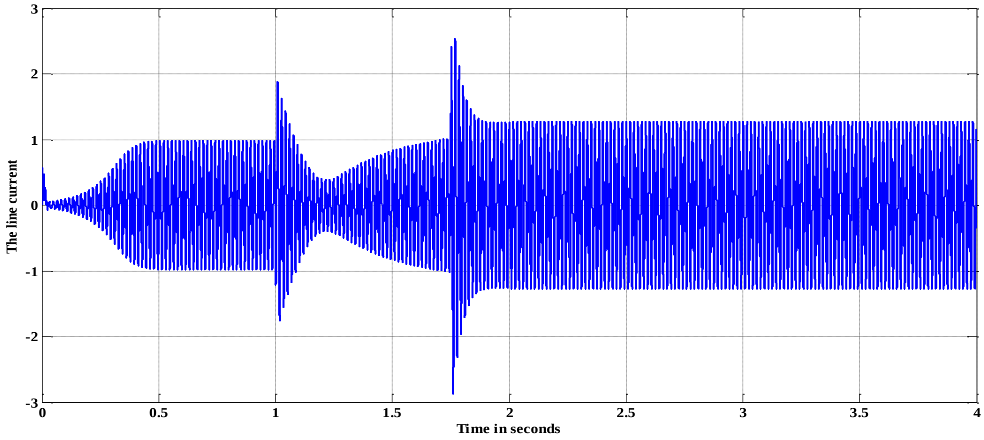


Figure 15. Line current with DSSC

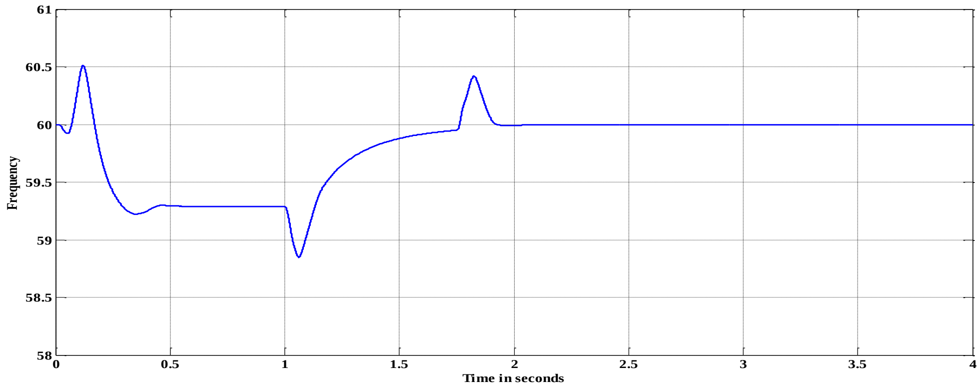


Figure 16. line frequency with DSSC

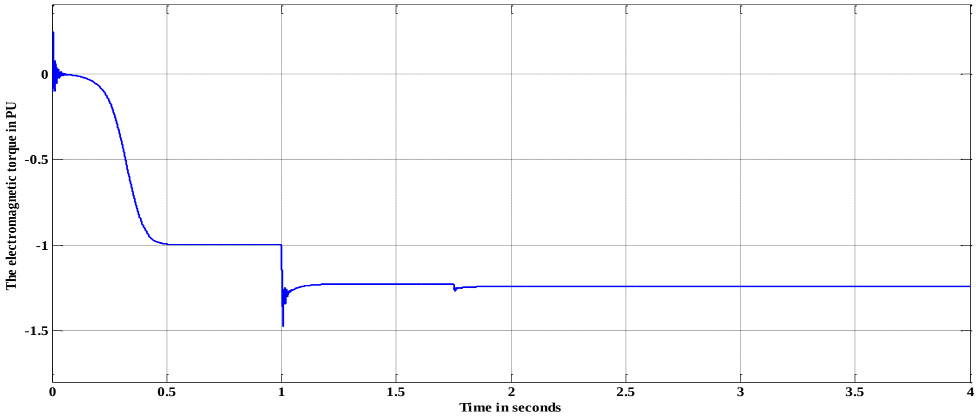


Figure 17. Electromagnetic torque with DSSC

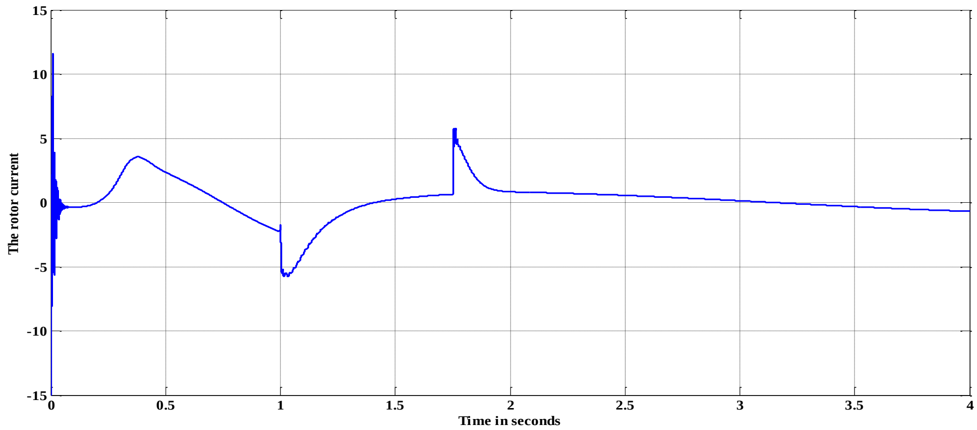


Figure 18. Rotor current with DSSC

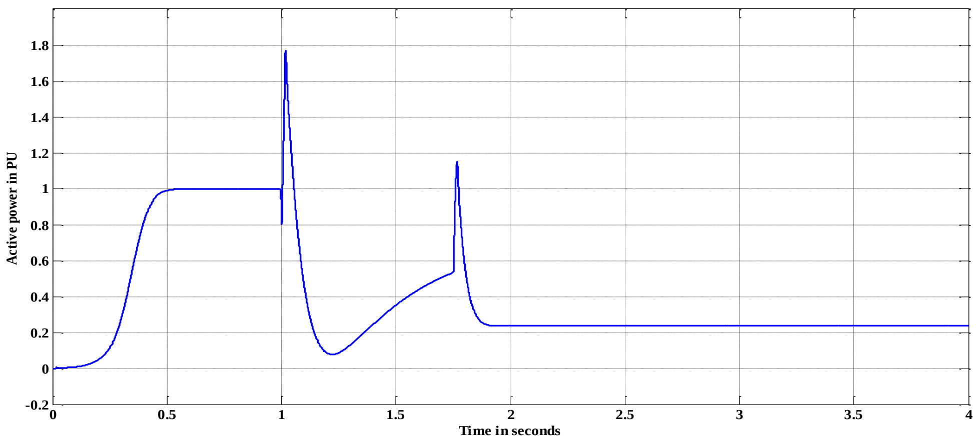


Figure 19. Active power output with DSSC

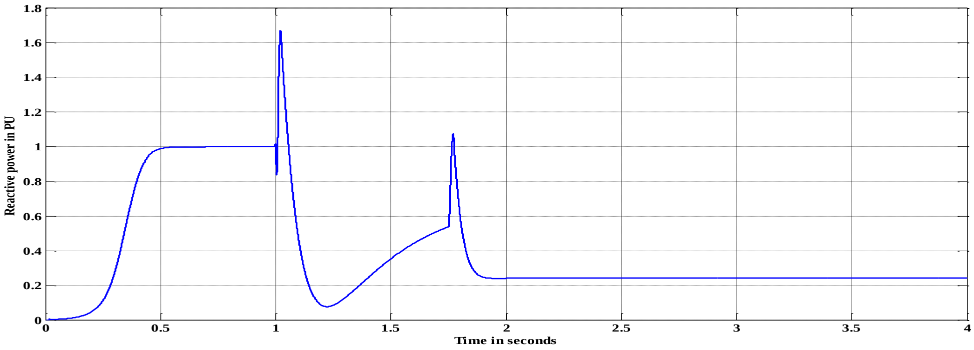


Figure 20. Reactive power output with DSSC

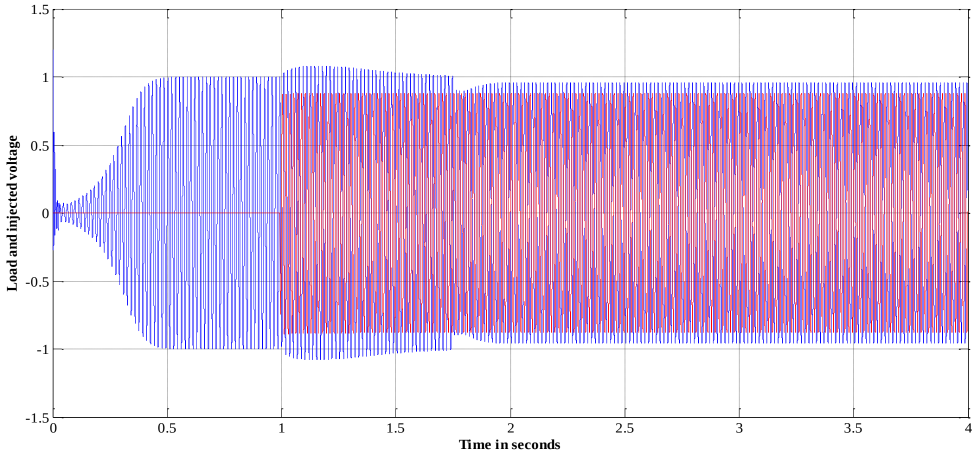


Figure 21. Injected voltage and load voltage

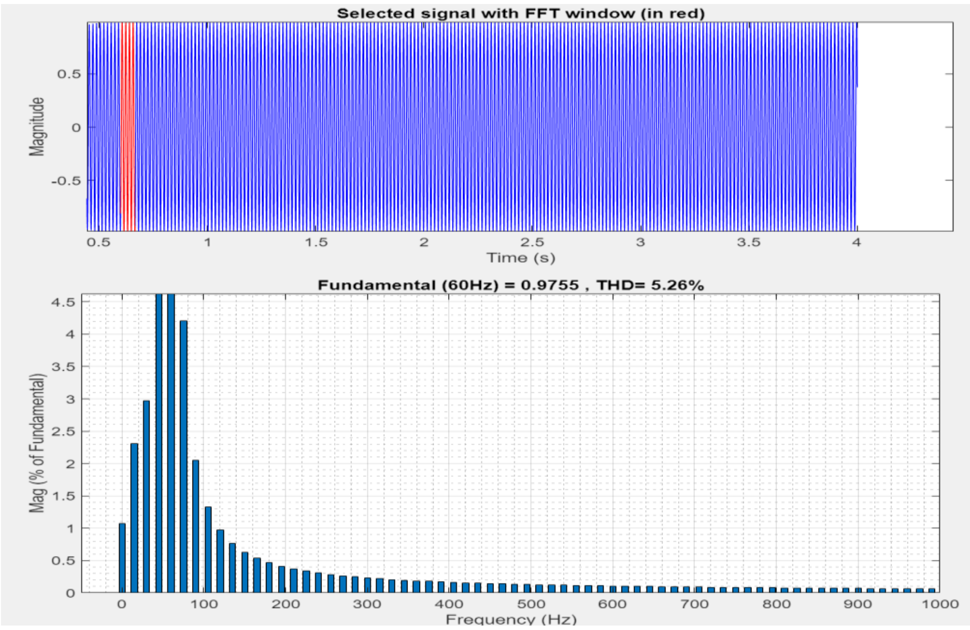


Figure 22. THD of the load voltage after injection

7. CONCLUSION

This manuscript proposes an NFC algorithm to support SEIG action using DSSC. To apply the theory of neuro fuzzy systems, an offline tuning algorithm is used. The Takagi-Sugeno fuzzy logic system was used to achieve a short computation time for the controller, which is likely to be implemented in real-time. The presented controller demonstrates its efficacy for increasing load voltage and regulating power influx toward the load. The simulation results demonstrate that the proposed controller can provide an acceptable presentation for DSSC operation.

REFERENCES

[1] E. Acha, C. Fuerte, H. Ambriz, and C. Angeles-Camacho, "FACTS Modelling and Simulation in Power Networks," *John Wiley & Sons Ltd*, pp. 21-23, 2004.

[2] R. Mathur and R. Varma, "Thyristor-based FACTS Controllers for Electrical Transmission Systems," *Wiley-IEEE Press Power engineering, Piscataway*, NJ, Mar, pp. 34-36, 2004.

[3] Hingorani and L. Gyugyi, "Understanding FACTS, Concepts and technology of flexible AC transmission systems," *IEEE Press*, pp. 172-174, 2000.

[4] B. Jena and A. Choudhury, "Voltage and frequency stabilisation in a micro-hydro-PV based hybrid microgrid using FLC based STATCOM equipped with BESS," *International Conference on Circuit, Power and Computing Technologies (ICCPCT)*, 2017, pp. 1-7, doi: 10.1109/ICCPCT.2017.8074291.

[5] A. J. Ali, M. Y. Sulaiman, L. A. Khalaf, and N. S. Sultan, "Performance investigation of stand-alone induction generator based on STATCOM for wind power application," *International Journal of Electrical and Computer*, vol. 10, no. 6, pp. 5570-5578, 2020, doi: 10.11591/ijece.v10i6.pp5570-5578.

[6] T. B. Kumar and M. V. G. Rao, "Mitigation of Harmonics and power quality enhancement for SEIG based wind farm using ANFIS based STATCOM," *International Conference on Smart Electric Grid (ISEG)*, 2014, pp. 1-7, doi: 10.1109/ISEG.2014.7005595.

[7] D. Chermiti and A. Khedher, "Voltage and Frequency Control of a Self-Excited Induction Generator using Bidirectional STATCOM Devoted to Rural Electrification," *10th International Renewable Energy Congress (IREC)*, 2019, pp. 1-6, doi: 10.1109/IREC.2019.8754570.

[8] Yahyaoui and Imene, "Advances in Renewable Energies and Power Technologies: Volume 1: Solar and Wind Energies," *Elsevier Science Ltd*, ISBN: 978-0-12-812959-3, 2018.

[9] B. Yang, G. Zeng, and Y. Zhong and Z. Su, " Power Quality Improvement of a Self-Excited Induction Generator Using NFPI Controller Based Hybrid STATCOM System," *2019 IEEE International Conference on Intelligent Techniques in Control, Optimization and Signal Processing (INCOS)*, 11-13 April 2019, doi:10.1109/INCOS45849.2019.8951424.

[10] Sanjay Dewangan and Shelly Vadhera, "Performance Improvement of Wind Turbine Induction Generator Using Neural Network Controller," Advances in Renewable Energy and Sustainable Environment, Springer Nature Singapore Pte Ltd. 2021, doi:10.1007/978-981-15-5313-4_16.

[11] Ezzeddine Touti, "Reactive power analysis and frequency control of autonomous wind induction generator using particle swarm optimization and fuzzy logic," *Energy Exploration & Exploitation*, 2020, Vol. 38(3) 755–782, doi:10.1177/0144598719886373.

[12] L. Qing and W. Zengzing, "Coordinated design of multiple FACTS controllers based on fuzzy immune co-evolutionary Algorithm," *IEEE Power & Energy Society General Meeting*, 2009, pp. 1-6, doi: 10.1109/PES.2009.5275629.

[13] M. Y. Suliman, M. T. Al-Khayyat, "Power flow control in parallel transmission lines based on UPFC," *Bulletin of Electrical Engineering and Informatics*, vol. 9, no. 5, pp. 1755-1765, 2020, doi: 10.11591/eei.v9i5.2290.

[14] Mohammed Y. Suliman, M. E. Farrag, and Sinan Bashi, "Design of fast real time controller for the SSSC based on takagi Ss - sugeno (TS) adaptive neuro-fuzzy control system", *Renewable Energy and Power Quality Journal*, Vol. 1, No. 12, pp 1025-1030, 2014, https://doi.org/10.24084/repqj12.575.

[15] Ahmed Tahir, Zakariya Rajab, and Ahmed Hammoda, "Genetic algorithm–based calculation of the excitation capacitance of a self-excited induction generator for stable voltage operation over load and speed variations," Wind Engineering, 2017, doi: 10.1177/0309524X17721998.

[16] Sanjay Dewangan and Shelly Vadhera, "Performance enhancement of a stand-alone induction generator-based wind energy system using neural network controller," *International Journal of Green Energy,* ISSN: 1543-5075 (Print) 1543-5083, 2020, doi: 10.1080/15435075.2020.1723594.

[17] Sanjay Dewangan, Giribabu Dyanamina, and Navin Kumar, "Performance improvement of wind-driven self-excited induction generator using fuzzy logic controller," Electrical Energy System, 20 June 2019, doi:10.1002/2050-7038.12039.

[18] M. Y. Suliman and M. Emad Farrag, "Power Balance and Control of Transmission Lines Using Static Series Compensator," *53rd International Universities Power Engineering Conference (UPEC)*, 2018, pp. 1-5, doi: 10.1109/UPEC.2018.8541894.

[19] V. Ponananthi and B. R. Kumar, "Three-phase STATCOM controller using D-Q frame theory for a three-phase SEIG feeding single phase loads," *2nd International Conference on Electronics and Communication Systems (ICECS)*, 2015, pp. 926-931, doi: 10.1109/ECS.2015.7125050.

[20] M. T. Al-Khayyat and M. Y. Suliman, "Neuro Fuzzy based SSSC for Active and Reactive Power Control in AC Lines with Reduced Oscillation," *Przeglad Elektrotechniczny*, vol. 1, no. 3, pp. 77-81, 2021, doi: 10.15199/48.2021.03.14.

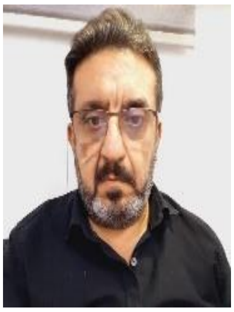
[21] Mohammed Y. Suliman, "Voltage profile enhancement in distribution network using static synchronous compensator STATCOM," *International Journal of Electrical and Computer Engineering*, vol. 10, no. 4, pp. 3367-3374, 2020, doi: 10.11591/ijece.v10i4, pp3367-3374.

[22] M. Y. Suliman and R. K. Antar, "Power Flow Controller Based on a New Proposed Statcom Controller," *International Journal of Engineering and Technology*, vol. 7, no. 4, pp. 3826-3829, 2018, doi: 10.14419/ijet. v7i4.17854.

[23] M. Y. Suliman, "Active and reactive power flow management in parallel transmission lines using static series compensation (SSC) with energy storage," *International Journal of Electrical and Computer Engineering*, vol. 9, no. 6, pp. 4598-4609, 2019, doi: 10.11591/ijece.v9i6, pp4598-4609.

[24] M. Y. Suliman and S. M. Bashi, "Fast response SSSC based on instantaneous power theory," *International Conference on Electrical Communication, Computer, Power, and Control Engineering (ICECCPCE)*, 2013, pp. 174-178, doi: 10.1109/ICECCPCE.2013.6998757.
[25] Hesham M. Fekry, Azza Ahmed Eldesouky, Ahmed M. Kassem, and Almoataz Y. Abdelaziz, "Power Management Strategy Based on Adaptive Neuro Fuzzy Inference System for AC Microgrid," *IEEE Access,* Volume 8, 21 October 2020, doi: 10.1109/ACCESS.2020.3032705.

BIOGRAPHIES OF AUTHORS



Mahmood T. Alkhayyat received his BSc, M.Sc. and Ph.D. degrees from Mosul university, Iraq in 1994, 1998 and 2018 respectively. Currently, he is a senior lecturer, in the technical college, northern technical university. His research interests, include power system assessment, power electronics, FACTS, renewable energy, and power system optimization. He can be contacted at email: m.t.alkhayyat@ntu.edu.iq.

Ziad Saeed Mohammed received his BSc, M.Sc. degrees from University of Technology and Ph.D. degree from University of Mosul, Iraq in 1990, 2001 and 2016 respectively. Currently, he is a lecturer, in the technical college, northern technical university. His research interests, include adaptive control, electronics devices, image processing, switching memory. He can be contacted at email: dr.ziadsaeed@ntu.edu.iq.

Ahmed J. Ali is a lecturer at department of power engineering technology/ engineering technical college/Mosul. He got BSc. and Msc. from Al-Technologia Unversity/Baghdad In 1995 and 2004 respectively in electrical engineering. He has finished his Ph.D. in electrical machines from university of Mosul in 2012 studying period. He is interested in adaptive and intelgent control systems, electric machines designe and drives. He can be contacted at email: ahmed.j.ali@ntu.edu.iq.