Comparative Analysis of PI, FOPI and Fuzzy Logic Controllers to Mitigate Voltage Sags Effects on an Induction Motors

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***Abstract*—The integer order (PI), fractional order PI (FOPI) and fuzzy logic (FL) controllers were used with the dynamic voltage restorer (DVR) to neutralize the impacts of voltage sags on an induction motor. DVR was used to protect the induction motor from symmetrical voltage sags. DVR with PI/FO-PI controller has a simple structure. Precise tuning of the gains in controller is a major issue being dealt with in the PI as well as FO-PI controllers. Changing system parameters and operating conditions do not render desired output with fixed gains. Fuzzy logic controllers are widely used to cover the variations in the machine parameters and operating environments. This study demonstrates the utility of a fuzzy logic controller in counteracting the ills of voltage sags on induction motors. Modeling and simulation of a DVR using PI/FO-PI and fuzzy logic controllers was designed in the MATLAB/Simulink. Dynamic state of the motor during sag and the voltage source inverter's switches are non linear. Fuzzy logic being a non-linear controller, excellent DVR output with it was achieved. Simulation results validated that DVR with fuzzy logic control system is fast, flexible and efficient for voltage sag compensation. Performance of the proposed controllers are evaluated and compared based on controller's efforts and time domain performance indices such as IAE, ISE and ITAE. Results show that proposed fuzzy logic controller provides a smoother mitigation of voltage sag with lesser controller effort and time domain indices.**

I. INTRODUCTION

Voltage sags in any industrial process lead to adverse effects on its efficiency, production and quality [1]. Three phase induction motor is a workhorse of electrical power industry because of its rugged structure, simplicity, low cost and reliability. Voltage sags caused by symmetrical/unsymmetrical faults on the power system affect the performance of induction motors in the form of transient in currents and torques [2]. Loss in speed, loss in electromagnetic torque, increase in other losses leading to drop in efficiency, temperature rise causing decrease in life of insulations, vibrations and acoustic noises etc. [3, 4]. In addition, voltage sags leading to tripping of induction motors connected directly to the supply affects the production and its economy [5, 6]. Hence it is imperative to minimize the impact of voltage sags in the system and the processes where the induction motor is used. As shown in Fig.1 a prominent tailor made device Dynamic voltage restorer (DVR) is meant to compensating the power quality problems related to voltage sags.

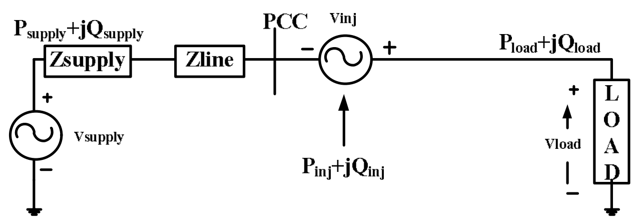


Fig 1. Distribution system with DVR

Installation of DVR is reported in [7, 8], to protect induction motor from frequent tripping because of the voltage sags in the refinery. The focus of this study was to design a controller that achieved a desired mitigation of voltage sag. The functioning of a control system solely rests on the control strategy employed. Therefore, fast transient response and steady state output are most critical essential attributes of a controller [9]. Different control methodologies linear and non-linear in nature are employed in the industry. The regulators viz. the ramp-comparison current, the synchronous PI, the state feedback [10] and the predictive and the dead-beat [11-13] make the linear controllers whereas the non-linear controllers include the neural network and the Fuzzy controllers [14, 15]. PID (proportional integral derivative) control mechanism is ideal for industrial operations thanks to its robust structure and reliability [16]. In recent times, growing interest for upgrading the execution of conventional PID has prompted extensive consideration towards FOPID controllers [17-19]. The efficiency of the controllers can be increased by introducing two degrees of freedom in the use of integrator and differentiator fractional orders imparting a greater elasticity to FO-PID [20-24].

In the present study the simulation of the DVR with PI, FO-PI and fuzzy logic controller was performed using

MATLAB/SIMULINK. The comparative analysis of PI, FO-PI and fuzzy logic controllers were performed to enhance the performance of DVR to mitigate the effects of voltage sags on an induction motor. In conventional PI controllers, the gains are fixed, hence give good performance at that operating point. When the operating point is changes due to change in system parameters, fault level, etc., parameters of PI controllers need to be redesigned. In the present study, the gains and orders of the controllers are fine-tuned using the FOMCON tool box available in the MATLAB [25]. In the absence of gain rescheduling of the PID/FOPID controllers, it is difficult to get optimum output if the non-linearity in the plant, load and frequent variations are present in the system. A PID/FOPID controller tuned to meet given performance criteria at one point may not encounter those criteria as variations in system take place. Owing to the ability to mitigate the variations in the parameters viz. load, non-linearity in the system/load, the fuzzy logic controllers is the viable alternative as also observed in the present study. The very basis of design of controllers is the reduction in time domain performance indices viz. Integral Absolute Error (IAE), Integral Square Error (ISE) and Integrated Time Absolute Error (ITAE) and the controller's efforts. Fuzzy logic controller gives superior results amongst all controllers.

II. INDUCTION MOTOR MODEL

A. Voltage Sag Detection Techniques and synchronisation

The set of voltage, flux and mechanical differential equations define the dynamics of a machine. The voltage equations transferred to the stator windings is written as in (1) and flux linkages of the motor can be expressed as in (2) and torque equation can be expressed as in (3).

$$\begin{bmatrix} V_{abcs} \\ V_{abcr} \end{bmatrix} = \begin{bmatrix} rs + pL_S & pL'_{sr} \\ pL'_{sr} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} I_{abcs} \\ I_{abcr} \end{bmatrix} \qquad (1)$$

$$\begin{bmatrix} \psi_{abcs} \\ \psi_{abcr} \end{bmatrix} = \begin{bmatrix} L_S & L'_{sr} \\ L'_{sr} & L_r \end{bmatrix} \begin{bmatrix} I_{abcs} \\ I_{abcr} \end{bmatrix} \qquad (2)$$

$$Te = J\frac{d\omega_r}{dt} + T_L + B\omega_r \qquad (3)$$

where,

V_{abcs}-the phasor of stator voltages; V_{abcr} - the phasor of rotor voltages; I_{abcs}-phasor of stator currents; I_{abcr} - phasor of rotor currents; ψ_{abcs} and ψ_{abcr}- stator and rotor flux respectively; Rs, Rr - stator and rotor resistances respectively; Ls, Lr - stator and rotor inductances respectively. Te-electromagnetic torque; T_L- Load torque; J- inertia of the system; B- friction co-efficient.

III. DYNAMIC VOLTAGE RESTORER

A. Voltage Sag Detection Techniques and synchronisation

The sag detection techniques at the disposal of a designer are the use of rms values, peak values, d-q transformation frame, Fourier Transform (FT) and Wavelet Transform (WT). The present study considered the transformation of the three phase voltages to a two dimensional (dq) frame for detection of voltage sags. Three-phase line voltages are converted in to their equivalent two-phase system called stationary reference frame using d-q transformation. Fig. 3 depicts the transformed synchronous reference frame using these quantities. In order to find information about phase angle and frequency of utility voltage, a phase locked loop (PLL) was used in the control scheme. Pcc voltages and load voltages were transformed to V_{dq} using Park's transformation as in (4)

$$\begin{bmatrix} V_{Ld} \\ V_{Lq} \\ V_{L0} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \mathrm{Cos}\,\theta & -\mathrm{Sin}\,\theta & \frac{1}{2} \\ \mathrm{Cos}\,(\theta - \frac{2\pi}{3}) & -\mathrm{Sin}\,(\theta - \frac{2\pi}{3}) & \frac{1}{2} \\ \mathrm{Cos}\,(\theta + \frac{2\pi}{3}) & -\mathrm{Sin}\,(\theta + \frac{2\pi}{3}) & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_{La} \\ V_{Lb} \\ V_{Lc} \end{bmatrix} \qquad (4)$$

Unit vectors are used to extract reference load voltages which are also converted into rotating frame.

Using (5) and (6), DVR control voltages are obtained.

$$V_{cd} = V_{sd} - V_{Ld} \qquad (5)$$

$$V_{cq} = V_{sq} - V_{Lq} \qquad (6)$$

The voltage error between reference DVR control voltages and actual DVR control voltages are calculated using (7) and (8).

$$V^*_{cd} = V^*_{sd} - V^*_{Ld} \qquad (7)$$

$$V^*_{cq} = V^*_{sq} - V^*_{Lq} \qquad (8)$$

In this study, the DVR voltage error obtained in (7) and (8) are compensated using PI, FO-PI and fuzzy logic controller. These compensated voltages are converted to abc frame using inverse Park's transformation which further used in SPWM pulses generation as shown in figure 2.

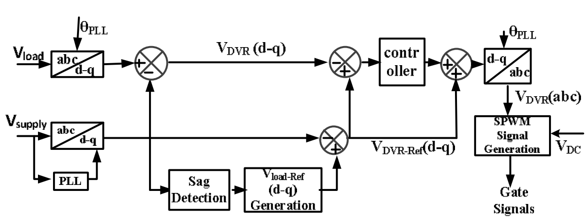


Fig 2. SRF based control for DVR

B. Methods of compensation

Methods of voltage compensations are: Pre-fault compensation, in-phase compensation and phase advanced compensation that depend upon different loading condition, types of sags, DVR power rating, etc. The pre-fault compensation technique was used in the present study. The phasor diagram of injection voltage compensation techniques is given in Fig. (3). Equations (9) and (10) gives injected voltage and its phase angle.

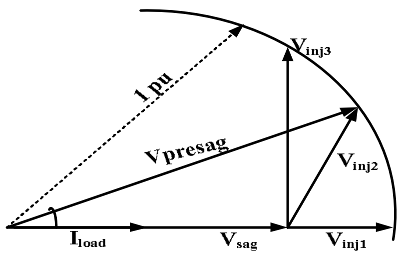


Fig 3. Phasor diagram of DVR injected voltages

$$\left|V_{inj}\right| = \left|V_{pre-sag}\right| - \left|V_{sag}\right| \quad (9)$$

$$\theta_{inj} = \tan^{-1}\left(\frac{V_{presag}\,\mathrm{Sin}(\theta_{presag})}{V_{presag}\,\mathrm{Cos}(\theta_{presag}) - V_{sag}\,\mathrm{Sin}(\theta_{sag})}\right) \quad (10)$$

C. Filter Design

In order to minimize the switching harmonics generated by the SPWM control of voltage source converters (VSC) the filters are inserted. Equation (11) describes the transfer function of the filter.

$$\frac{V_c(s)}{V_{inv}(s)} = \frac{1}{s^2 L_f C_f + sR_f C_f + 1} \quad (11)$$

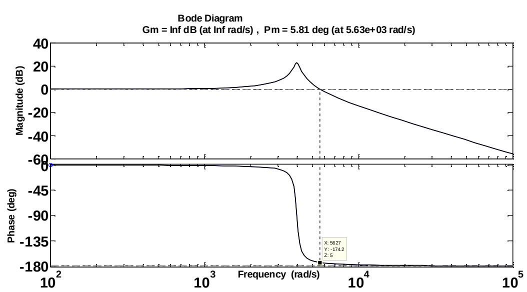


Fig 4. Fuzzy logic controller

Filter parameters are tuned with the help of frequency response shown in Fig. (4). Tuned filter components are: f=3.5m; Rf=1 Ω and Cf=18μF.

IV. DVR CONTROLLER DESIGN

Since the execution of the general control framework to a great extent relies on the quality of the connected control technique, a superior controller with quick transient reaction and great steady state attributes is required. In the present study three types of control systems have been proposed viz. PI, FO-PI and FL controllers. Conventional PI and FOPI controllers are the linear whereas the fuzzy logic controllers are the non-linear type of controllers.

A. PID Controller

PID controllers are universally employed and are the vital parts of industrial automation. They are used as a standard check to compare with other control plans. Equation (12), gives the controller's transfer function, where, K_p, K_i and K_d are the proportional, integral and differentiator gain values.

$$G_{PID}(s) = K_p + \frac{K_i}{s} + K_d \quad (12)$$

In this study, parameters of the PI controller shown in Fig. (3), viz. K_p =2 and K_i =1.5 are tuned up using FOMCON toolbox. Equation (13) shows PI controller's transfer function,

$$G_{PI}(s) = \frac{2s + 0.9}{s} \quad (13)$$

B. FO-PID Controller

The generalized form of the fractional order PID controller in the form $PI^{\lambda}D^{\mu}$ was first introduced in [17]. The fractional calculus is the basis of fractional order controllers due to its ability to tackle the real powers of operators (differential or integral). The definition of fractional calculus as generalized in (14) is universally adopted.

$$D^{\alpha} = \begin{cases} \frac{d^{\alpha}}{dt} & \alpha > 0 \\ 1 & \alpha = 0 \\ \int_0^t (d\tau)^{-\alpha} & \alpha < 0 \end{cases} \quad (14)$$

where, α is a real number.

Fig. (5) depicts the FO-PID controller's block diagram and (15) describes its transfer function.

$$G_{FO-PID}(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu}, (\lambda, \mu > 0) \quad (15)$$

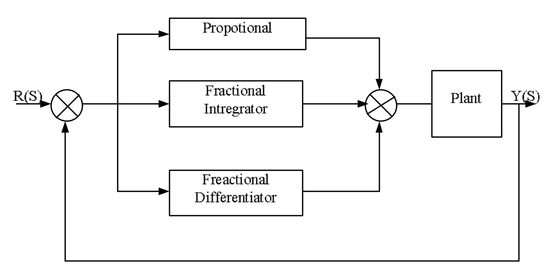


Fig 5. Fractional order controller

K_P, Ki, K_d- are controller gains and λ and μ are the orders of integrator and differentiator respectively. If order of integrator (λ) and differentiator (μ) is one, then (15) changes to transfer function of PID controller as presented in (13).

In this study, gain and order namely, K_P=2 and K_I=1.5 and λ=0.9 were chosen with the help of MATLAB - FOMCON toolbox. Equation (16) gives the fractional order controller's transfer function.

$$G_{FO-PI}(s) = \frac{2s^{0.9} + 1.5}{s^{0.9}} \qquad (16)$$

C. Fuzzy Logic Controller (FLC)

The concept of fuzzy logic and its applications are time tested and pondered upon for their merits and limitations. The aim of fuzzy logic has been to mimic our computers like human beings. The input and output variables are determined by fuzzy sets and its membership functions. Its knowledge domain has a database defining various variables. With the help of rules of knowledge base, it maps fuzzy input variables E with fuzzy output U. Fuzzy principle is employed to determine the output associated with individual rule. The fuzzy outputs arrived at from individual rule are pulled and defuzzified to develop a crisp output. Fig. (6) shows a basic structure of an FLC. In this study, two input variables were incorporated whereas output variable was a signal to control SPWM pulses [Fig. (7)].

a. Implication Relations

An implication relation (R(x/y)) is the analytical form of an if/then rule. Following are the implication relation operators (Φ) commonly used in FLCs.

Zadeh Max-Min Implication Operator:

$$(\Phi)[\mu_A(x), \mu_B(y)] = (\mu_A(x) \wedge \mu_B(y))(1-\mu_A(x))$$

Mamdani Min Implication Operator:

$$(\Phi)[\mu_A(x), \mu_B(y)] = (\mu_A(x) \wedge \mu_B(y))$$

Larson Product Implication Operator:

$$(\Phi)[\mu_A(x), \mu_B(y)] = \mu_A(x) \times \mu_B(y)$$

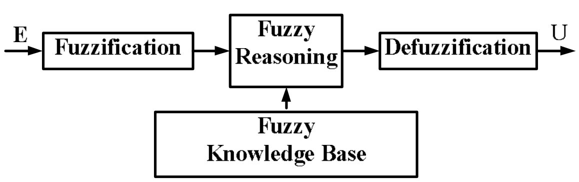


Fig6. Fuzzy logic controller

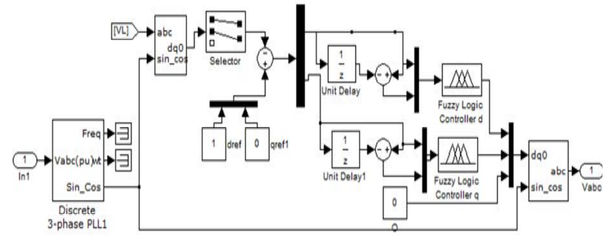


Fig 7. Fuzzy logic control scheme

In the present study, Mamdani Min implication relation was used. Forty nine fuzzy rules were employed to associate with each combination of input-output variables.

The width of zero level error membership function can be used to reduce the steady state error. Keeping this membership function thin, the steady state error was maintained at a low level. Centroid type of defuzzification is used which gives switching signal for SPWM. Figure (8) shows the surface viewer of the proposed FLC.

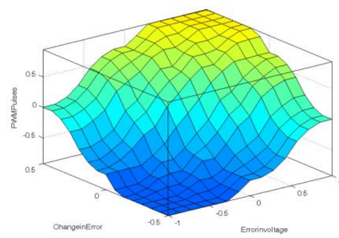
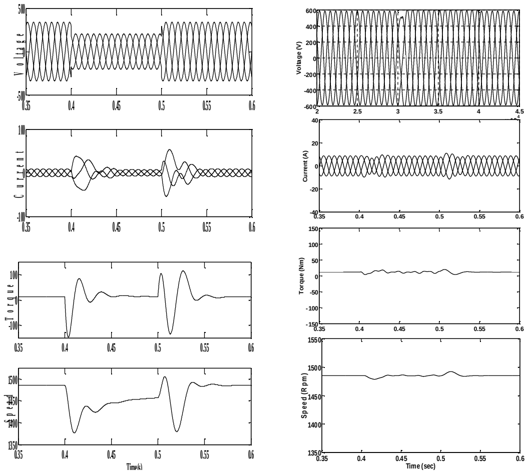


Fig 8. Surface viewer of FLC

V. Simulation Results

The proposed DVR with PI, FOPI and fuzzy logic controller were simulated using MATLAB/SIMULINK. DVR was inserted between 440V, 50 Hz supply and the 3-phase induction motor. With a view to verify the reaction of symmetrical voltage sags, an induction motor was modeled using the Park model [26] with parameters mentioned in Table 1 [27]. A symmetrical voltage sag of 40 per cent was considered, which starts at 0.4 sec and lasts for five cycles. The gain and orders of the PI and FOPI controllers are as mentioned in Table 2. The effects of voltage sags on voltage, current, torque and speed of an induction motor are given in Figs. (9a) whereas the Figs. (9b) show the injected voltage and restored voltage of the system using fuzzy logic controller. Figs. (10-12) shows the control signal efforts of PI, FOPI and FL controllers whereas Table 3 shows the time performance induces viz. IAE, ISE and ITAE for the three controllers.



(a) (b)

Fig 9. (a) Symmetrical voltage sag effects on an Induction motor 9 (b) Restored voltage due to FL controller

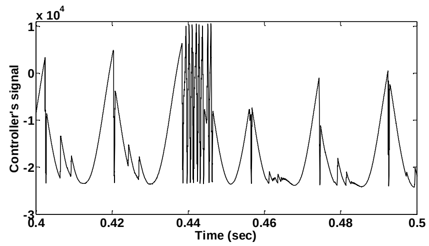


Fig 10. PI controller's effort

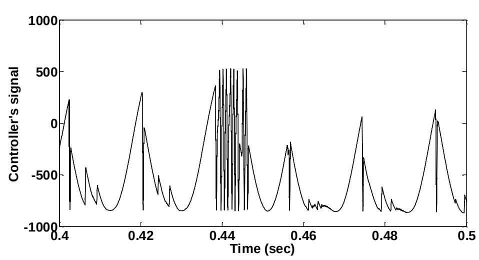


Fig. 11. FO-PI controller's effort

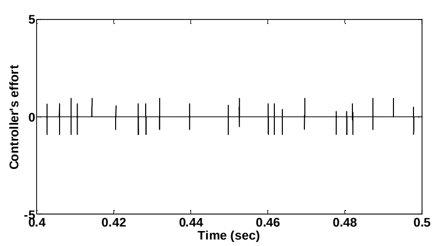


Fig 12. Fuzzy logic controller's effort

TABLE I. PARAMETERS OF 3-PHASE INDUCTION MOTOR

T_L	R_s Ω)	R_r Ω)	X_s Ω)	X_r Ω)	X_m(Ω)	J
11.9	0.435	0.816	0.754	0.754	26.13	0.089

TABLE II. GAIN AND ORDER VALUES OF CONTROLLERS

Controllers	K_P	K_I	**λ**	**μ**
PI	2	1.5	1	1
FO-PI	2	1.5	0.9	1

TABLE III. TIME BASED PERFORMANCE INDICES FOR ERROR SIGNAL

Controllers	**IAE**	**ISE**	**ITAE**
PI	546.9	1.78×10^5	358.9
FO-PI	193.6	5.43×10^4	73.72
FLC	81.16	2.12×10^4	38.33

VI. CONCLUSION

Fully automated production processes require a precisely regulated supply voltage. In the absence of this the complete process may get shut down due to a transient drops in voltage leading to losses in production and economics. Voltage sag affects the performance of three-phase induction motor adversely. DVRs ensure the viable alternative to safeguard the induction motors from voltage sags and other power quality issues. In this study modeling and simulation of DVR with fuzzy logic control is performed in MATLAB/SIMULINK and the findings are out wayed with PI and FO-PI controllers. A major limitation of PI and FO-PI controllers is that it requires frequent correction in tuning of the controller gains in tune with the changes in parameters. Many control objects are of fractional order, therefore FO-PI's application is useful. The PI/FO-PI controllers may fail to make amends required for controlled performance with fixed gains in situations of variable system parameters. Complex mathematical modeling of the system is required. Fuzzy logic controller covers a wide range of operating conditions hence integrating it with DVR becomes simple, fast and adaptive control mechanism in order to safeguard the induction motor from all types of power quality issues(viz. sag, swell, harmonics, flicker, etc.). By changing the membership functions and rules you can get different response characteristics. Fuzzy logic controller's effort is quite less as compare to other two controllers. Again the time performance indices of fuzzy logic controller are less compared with its counterpart. Hence fuzzy logic controller is most efficient, flexible and adaptive controller to mitigate sag effects on an induction motor.

REFERENCES

[1] Bollen, M H.J, "Understanding Power Quality Problems-voltage Sags and Interruptions," New York, NY, USA: IEEE press, 2000.

[2] Pedra, J., F. Córcoles, and L. Sainz. "Effects of unsymmetrical voltage sags on squirrel-cage induction motors." IET Generation, Transmission and Distribution 1, no. 5 (2007): 769-775.

[3] Gomez, J, Medhat M. Morcos, Claudio A. Reineri, and Gabriel N. Campetelli. ``Behavior of induction motor due to voltage sags and short interruptions." IEEE Transactions on Power Delivery 17, no. 2 (2002): 434-440.

[4] Guasch, Luis, Felipe Córcoles, and Joaquín Pedra. ``Effects of symmetrical and unsymmetrical voltage sags on induction machines." IEEE Transactions on power delivery 19, no. 2 (2004): 774-782.

[5] Patne N and Thakre K, "Effect of transformer type on estimation of financial loss due to voltage sag PSCAD/EMTDC simulation study" IET Gener Transm Dis 2010; 4: 104-114.

[6] ElShennawy, Tarek I., Mahmoud A. El-Gammal, and Amr Y. Abou-Ghazala. ``Voltage sag effects on the process continuity of a refinery with induction motors loads." American Journal of Applied Sciences 6, no. 8 (2009): 1626.

[7] ElShennawy, Tarek Ibrahim, Amr Yehia Abou-Ghazala, and Mahmoud El-Gammal. ``Voltage Sag Effects on a Refinery with Induction Motors Loads." ELEKTRIKA 11, no. 2 (2009).

[8] Nielsen, John Godsk, and Frede Blaabjerg. ``"A detailed comparison of system topologies for dynamic voltage restorers." IEEE Transactions on Industry Applications 41, no. 5 (2005): 1272-1280.

[9] Choi, S. S., B. H. Li, and D. M. Vilathgamuwa. ``Design and analysis of the inverter-side filter used in the dynamic voltage restorer." IEEE transactions on power delivery 17, no. 3 (2002): 857-864.

[10] Jeong, Jong-Kyou, Ji-Heon Lee, and Byung-Moon Han.``Three-phase line-interactive dynamic voltage restorer with a new sag detection algorithm." Journal of Power Electronics 10, no. 2 (2010): 203-209.

[11] Omar, Rosli, and N. Rahim. ``New configuration of a three phase dynamic voltage restorer (DVR) for voltage disturbances mitigation in electrical distribution system." Arabian Journal for Science and Engg (2012): 1-16.

[12] Li, Yun Wei, D. Mahinda Vilathgamuwa, Frede Blaabjerg, and Poh Chiang Loh. ``A robust control scheme for medium-voltage-level DVR implementation." IEEE Transactions on Industrial Electronics 54, no. 4 (2007): 2249-2261.

[13] Jurado, Francisco, and Manuel Valverde. ``Fuzzy logic control of a dynamic voltage restorer." In Industrial Electronics, 2004 IEEE International Symposium on, vol. 2, pp. 1047-1052. IEEE, 2004.

[14] Teke, A., K. Bayindir, and M. Tümay. ``Fast sag/swell detection method for fuzzy logic controlled dynamic voltage restorer." IET generation, transmission and distribution 4, no. 1 (2010): 1-12.

[15] Åström, Karl Johan, and Tore Hägglund. ``PID controllers: theory, design, and tuning." (1995).

[16] Podlubny I, "Fractional order systems and Fractional order controllers,"In: Institute of Experimental Physics, Slovak Academy of Sciences, Kosice (1994).

[17] Monje, Concepción A., YangQuan Chen, Blas M. Vinagre, Dingyu Xue, and Vicente Feliu-Batlle. ``Fractional-order systems and controls: fundamentals and applications. Springer Science and Business Media." 2010.

[18] Das, Shantanu. ``Functional fractional calculus. Springer Science and Business Media." 2011.

[19] Khubalkar S, A Chopade, A Junghare, Mohan Aware, and Shantanu Das. "Design and realization of stand-alone digital fractional order PID controller for Buck converter fed DC motor." Circuits, Systems, and Signal Processing 35, no. 6 (2016): 2189-2211.

[20] Khubalkar S, Junghare A, Aware M, Das S. Modeling and control of permanent magnet brushless DC motor drive using fractional order proportional integral derivative (FOPID) controller. Turk J Electr Eng CO 2017: 1-29.

[21] Khubalkar SW, Chopade A, Junghare AS, Aware MV, Das S. Design and reliazation of stand-alone digital fractional order PID controller for buck converter fed dc motor. Circ Syst Signal Pr 2016; 35: 2189-2211.

[22] Pandey S, Dwivedi P, Junghare A. Anti-windup fractional order $PI^{\lambda}D^{\mu}$ controller design for unstable process: a magnetic levitation study case under actuator saturation. Arab Journal Sci & Eng 2017; 1-15.

[23] Dwivedi P, Pandey S, Junghare A. Performance analysis and experimental validation of 2-DOF fractional order controller for under actuated rotary inverted pendulum. Arab Journal of Sci & Engg 2017; 1-25.

[24] A. Teplijakov, E. Petlenkov, and J. Belikov, ``Fomcon: a matlab toolbox for fractional-order system identification and control," International Journal of micro-electronics and computer science, vol.2, no. 2, pp.51-62, 2011.

[25] Pedra, J., I. Candela, and L. Sainz. ``Modelling of squirrel-cage induction motors for electromagnetic transient programs." IET electric power applications 3, no. 2 (2009): 111-122.

[26] Krause, P. C., Wasynczuk, and S. D. Sudhoff. "Analysis of electric machinery and drive systems". 2002.