Adaptive PI control of Electric Springs For Voltage Regulation Under Dynamic Load Changes

K.K.Deepika, J. Vijaya Kumar, G. Kesava Rao, Seelam Chaitanya

Abstract**:** ***Due to continuous distributed generation development technology, the accessibility of wind, solar and also the renewable energy sources tends to intensify. To suppress the voltage fluctuation caused by the distributed generation electric springs had been developed. In this article an adaptive control of Electric spring is proposed, in which the gains of the PI controller are optimised by TLBO to maintain constant voltage across critical load. The proposed strategy is tested for dynamic changes in the non-critical load. Simulation results show that, for voltage fluctuations caused by the DGs and also with the dynamic load changes, ES with adaptive controller stabilize the bus voltage effectively, over ES with Fuzzy Logic Control and traditional PI control.***

Index Terms**:** ***Electric Spring, TLBO, Tuning of PI controller.***

I. INTRODUCTION

The energy domain has become a conspicuous topic in global research due to the escalating prominence of energy and environment. So due to its important features the primary energy may be the extensive application of renewable sources. When DG supplies to the active distribution network, it reduces the transmission power ratings. DG has strong fluctuation due to solar energy and wind energy, which cause severe damage on the working of power system, and also increases the occurrence of failure in the system. Control of reactive power and energy storage [1] are the two viable solutions. Among these two reactive compensation technology cannot meet DG scenario much effectively, and energy storage technology (battery) can solve the voltage fluctuation in an effective manner as the current capacity is small but leads to high installation cost and effect on environment.In order to overcome these problems, Prof. Shu Yue (Ron) of Hong Kong University and the other members had introduced the analogy to mechanical spring that is Electric Spring (ES) [2]. ES can reduce the fluctuations and maintain the stabilized voltage, with the variations in renewable power generation capacity. [3] Discusses how PI controller post gain varies with the output current of ES to restrain voltage fluctuations. In [4], 0°/180° phase control technique is implemented to limit fluctuations in active power at the distribution network, using ES. In [5], performance of ES with droop control and coordinated droop control for voltage control is compared by considering European LV network.

In general, parameters of the PI controller have fixed values. To stabilize the voltage across critical load, for variations in the set point, parameters of the PI controller must be optimized dynamically. In the regulatory layer, tuning process involves refinement of control parameters to reduce the error. Conventional mathematical methods like Ziegler-Nicholas and Cohen-Coon methods, did not yield anticipated results. Advancements in the fields of metaheuristic optimization algorithms, led to improved tuning of PI controllers. This paper implements Teaching-Learning Based Optimization to determine optimal control gains. Advantage of TLBO is that it does not require any algorithm parameters for execution. Tuning of PI controllers with TLBO algorithm has been extensively applied in the last 7 years in diverse fields [6]-[12].

This paper presents tuning of PI controller with TLBO algorithm applied to the operation of Electric Springs in Distribution Systems. Main contributions of the paper are to highlight the robust and fast response of proposed adaptive controller to voltage fluctuations caused by intermittent power sources and dynamic load conditions. Robustness of the proposed adaptive PI controller for ES is highlighted by the comparison of obtained results with the conventional PI and Fuzzy Logic controllers.

II. ELECTRIC SPRINGS

A British Physicist Robert Hook had invented the" Mechanical Spring" concept, and three centuries hence, the mechanical spring had been used in electrical equipment and was named as "Electrical Spring".

The two types of springs are the mechanical spring and the electrical spring. The mechanical spring is a device that stores mechanical energy to provide mechanical support for damping the mechanical oscillations.

Revised Manuscript Received on August 05, 2019

K.K.Deepika, Assistant Professor, Vignan's Institute of Information Technology, Visakhapatnam, Andhra Pradesh & Research Scholar, KLEF, Vijayawada, Andhra Pradesh.

J.VijayaKumar, Assoc. Professor, Dept. of EEE, ANITS, Visakhapatnam, Andhra Pradesh.

Dr.G.Kesava Rao, Professor, Dept. of EEE, KLEF, Vaddeswaram, Andhra Pradesh.

S.Chaitanya, PG student, Vignan's Institute of Information Technology, Visakhapatnam, Andhra Pradesh.

Energy stored in a mechanical spring, P.E. is due to the stretched force applied, F and the deviation, x is proportional to its elasticity measured by spring constant, k, These terms are related as:

$F = -kx$ (1)

$P.E. = (1/2)\ kx2$ (2)

An electric spring can also be described from the Hooke's law of mechanical spring. It is a type of reactive power compensator which can be used to improve the voltage profile of the power system [10].Electric Spring provides voltage boost an also supports the voltage suppression. It distributes the voltage simultaneously on the demand side through the noncritical load management in case of occurrence of the fluctuations by the renewable energy sources. Loads are categorised as non-critical loads that are less sensitive to the voltage fluctuations and the critical loads known as voltage sensitive loads. Electric Spring injects the controllable voltage in series with the noncritical loads in order to implement the constant voltage across the critical loads

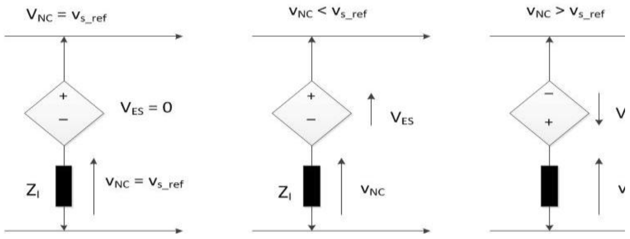
Thus, beside voltage control, the power consumed by the noncritical load is also modulated according to the input power resulting in frequency regulation.ES can also lower the energy storage requirements by up to 50% [11]. Capacitor in the ES, replaced with batteries on the DC side improve the power quality in the distribution system [12]. As the grid is very sensitive, connected equipment cannot tolerate the fluctuations beyond certain limits. Renewable energy, that is intermittent in nature, if directly connected to the grid may lead to the voltage collapse. So it is necessary to limit the voltage fluctuations in energy source. The reactive power and thereby voltage variations in the distribution lines can be controlled by ES thereby improving the stability of the system [13].The electric spring can be used as current controlled voltage source, that boost the voltage to a required level in case of voltage dip across critical loads and suppresses the excess voltage during over voltage.

On a whole, Electric Springs provides electric support to voltages by storing electrical energy and damping electrical energy oscillations. As mechanical spring provides the mechanical force in either directions during the change in displacement from the idle state, the electric spring integrated in series with the non-critical load can be synchronized to boost the voltage in under voltage conditions (Capacitive mode of ES) or suppress the voltage in case of over voltages (Capacitive mode of ES), to maintain constant PCC voltage, as illustrated in Fig. 1. This is achieved by regulating the charge, q stored in the capacitor, as represented in equations 3 and 4.

From equation (1) and (2),

$q = -Cv_a$ for Capacitive mode (3)

$q = Cv_a$for Inductive mode (4)



Neutral Capacitive mode Inductive mode

Fig.1. Various modes of operation of an ES

Where q is the electric charge stored in a capacitor with capacitance 'C', is the potential difference across the capacitor and i_c is the current flowing in the capacitor. The energy storage capacity of the electric spring can be formulated as

$q = \int i_c dtdt$ (5)

$P.E. = \frac{1}{2} Cv_a^2$. (6)

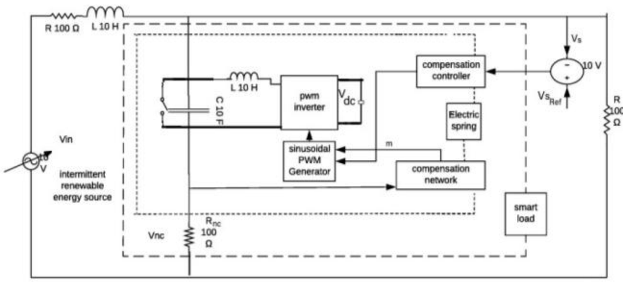


Fig.2. Schematic representation of controller of ES

In reference with Kirchhoff's law, vector equation can be given as, $V_c = R_{NC}I_{ES1} + V_{ES}$ (7)

The objective to maintain critical load voltage (V_2) constant is achieved by regulating both magnitude and phase angle of the injected current. In case of under voltage, current will lead voltage vector by 90^0 for voltage boosting and vice-versa.

III. TEACHING LEARNING BASED OPTIMIZATION

Whenever a variation in the critical voltage occurs, gain values of conventional PI controller have large values and invariable. This hinders the performance of PI controller to find a steady operating point due to the large adjustment step. Consequently, regulatory performance of the controller decreases significantly. This initiates to the need of adaptive adjustment of PI controller's parameters with the variations in the set point. In this paper, PI controller is made adaptive by the implementation of TLBO algorithm.

A. Introduction to TLBO

Many optimization techniques are available in research for the tuning of PI controller. They include mathematical methods and computational intelligence based algorithms. Operations of all the evolutionary and the swarm based algorithms demand regulatory parameters like population size, number of generations, elite size etc. As each of these optimization algorithms require their own specific parameters rather than the TLBO [14].For example, the GA describes the fitness value and uses mutation probability crossover probability and selection operator. Particle Swarm Optimization describes the behaviour of the birds for searching food, Artificial Bee Colony describes the behaviour nature of honeybee, Ant colony optimization explains the behaviour of ants to reach the source from destination. In this paper, Teaching based optimization is implemented to maintain the global solutions for continuous non-linear functions with less computational effort. Basically TLBO based algorithm depends upon the influence of the teacher on the output of the learners in a class and is independent of any parameters to be tuned. It showcases a high convergence rate as TLBO uses the best solution of the iteration to modify the current solution. In this paper, one of the advanced technique, Teaching-learning based optimization is implemented.

Teacher Phase:

During the teacher phase, a teacher attempts to improve the mean result of the classroom (M_1). As the teacher fails to achieve this, next attempt is initiated to any other value M_2 that is better than M_1. At any iteration i, consider M_i as mean and as the teacher. Now T_i will make an effort to improve existing mean M_i towards a new mean, M_{new}. Difference between the existing mean and new mean is given by

$$Difference\_Mean_i = (M_{new} - T_F M_i) \quad (8)$$

Where r_i is assigned randomly in the range [0, 1]. T_F is teaching factor governing the mean value it takes the value, either 1 or 2. Thus, the current solution is updated:

$$X_{new} = X_{old} + Difference\_Mean_i \quad (9)$$

In this classroom learning environment, teacher is considered to be the most intelligent person and can be known as best learner and this is shown by T_A. Teacher aims to disseminate knowledge among the learners, to improve the knowledge level of the learners in the class. The process proceeds towards a new mean M_B from the existing class mean, M_A by means of increasing the learners' knowledge level. Then, a new teacher T_B, of higher knowledge ass shown in curve-2 is considered.

Learner phase:

In the next phase of the TLBO algorithm, learners sharpen their knowledge by mutual interactions. Pairs of the learners is formed on a random basis. A learner gains knowledge if the other learner has more. Mathematical representation of updating the learning among learners M_i, M_j , is expressed as:

If learner M_i has more knowledge than M_j, that is,

$(M_i) > (M_j)$, then , M_{new}, = M_{old} + $(M_i - M_j)$, (10)

Else, for $(M_i) < (M_j)$, then, $M_{new} = M_{old} + (M_j - M_i)$. (11)

Accept M_{new} if it gives better function value.

B. Implementation of TLBO in control of Electric Springs

TLBO, a nature-inspired optimization algorithm, population consists of different values of design variables. Here, the design variables - gain values of PI controller are the various subjects opted by the learners, learners' outcome represents the fitness function. Teacher is corresponds to the best value of Kp and Ki obtained so far. Objective is to reduce the error value which is the output of the PI controller, as illustrated in Fig. 3.

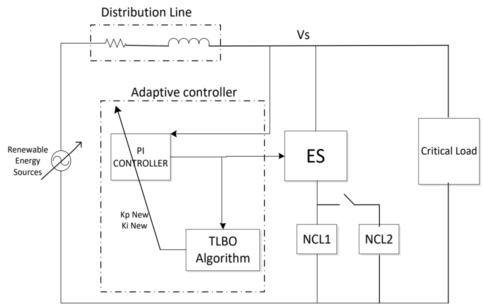


Fig.3 Implementation of adaptive controller for ES

IV. SIMULATION AND ANALYSIS

A. System parameters

To justify the voltage regulation capability of the proposed Adaptive PI controller, a model as shown in Fig. 3 is simulated in MATLAB/ Simulink environment, where the random variation in output of the Distributed generation source is represented by a three phase programmable voltage source as shown in Fig. 4. Voltage sag of 20% in the source is emulated from 0.5 to 1 seconds and voltage swell during 1.5-2 seconds. Dynamic changes in smart load is also considered along with the voltage fluctuations. This is included by switch On/Off of the second non-critical load, NCL2. Table II represents the diversity in the attributes simulated to analyze the operation of ES in voltage boosting and reduction modes. All the non-Critical and critical loads are assumed to be linear.

A distribution line of 1 km is used for simulation test [15]. Real and reactive power (P and Q) generated by renewable energy generation is emulated by a three-phase programmable voltage source. Distribution line of 1 kilometer with R-L values as given in Table I is simulated. Basic parameters of Electric Spring and PI controller are also detailed in Table I. Voltage on LV side is considered as 220 V. The simulations have been carried out in Matlab/Simulink environment for voltage fluctuations.

TABLE I. Simulation system specifications

Specifications of Distribution Line, Non-critical load unit		Specifications of Electric Spring	
Line Inductance (mH/km)	1.22	Inductance (mH)	5
Line Resistance(Ω/km)	0.1	Capacitance (μF)	13.2
Non- critical Load (Ω)	50.5		
Critical load Z (Ω)	53	PI Controller (Initial values)	
Line Inductance (mH/km)	1.22	K_p	2
Line Resistance(Ω/km)	0.1	K_i	1.5

TABLE II. Attributes simulated in the study

Time instants		Attributes
A to B	0.5-0.75sec	20% Decrease in Line Voltage
B to C	0.75-1 sec	Switch-On of NCL2
C to D	1-1.5sec	Line Voltage restored to normal
D to E	1.5-1.75 sec	20% Increase in Line Voltage
E to F	1.75-2 sec	Switch-OFF of NCL2
F to G	2 -2.5 sec	Line Voltage restored to normal

A. Simulation of TLBO algorithm in control of Electric Springs

The variation in line voltage with the variation in DG is shown in Fig. 5. In this subsection the procedure to implement TLBO to obtain best values of PI controller has been described. In the case of design of PI controller, the objective function is to minimise the error between the reference value of Vs and its actual value. In the initialization phase, population size is considered as 500, subjects of the learners or the design variables are Kp and Ki values. Both elements of the learner is initialized randomly within the limits of 1e6 and -1e6. Objective function of each learner is evaluated and elite learner is identified. This enables to calculate the mean of each design variable. Then, each learner is modified and objective function with modified learner calculated. Initial gain values of PI controller for ES are considered as Kp=2, Ki = 1.5. Best values obtained after the first iteration of TLBO algorithm are set to the PI controller and further simulation is carried out. Total simulation time is distributed into 6 time intervals as detailed in Table III. Voltage regulation by traditional PI control, Fuzzy logic control and adaptive PI control are can be analysed from Fig. 4.

TABLE III. Time intervals in simulation

Time instants		Attributes
A	0.5 sec	Initiation of Sag in Line Voltage (1 pu to 0.8pu)
B	0.75 sec	Switch-On of NCL2
C	1sec	Line Voltage restored to Normal
D	1.5 sec	Initiation of Swell in Line Voltage (1 pu to 1.2pu)
E	1.75 sec	Switch-OFF of NCL2
F	2 sec	Line Voltage restored to Normal

Initiation of Voltage Sag

With the reduction in reactive power from the DG Source, reduction in the line voltage is simulated from 0.5 sec to 1 sec, as shown in Fig. 5. This initiates ES to operate in voltage support mode that is clearly shown in Fig. 6. ES injects a voltage of 40volts in series with the Non-critical load voltage, to restore the line voltage back to its nominal value of 220 Volts. From Fig. 7 it can be clearly understood that ES succeeds to operate in voltage support mode by absorbing real power and injecting reactive power into the system. The adaptive controller operates in 0.05 sec from the instant of voltage sag that is very less when compared with 0.1 second required by conventional PI controller and 0.04sec required by Fuzzy Logic controller, illustrated in Fig. 4.

Switch -On of load under voltage sag condition

During the under-voltage condition ES injects inductive current from the DC source, thereby increases the voltage across smart load to nominal voltage. When another Non-critical load is added at instant B, the net resistance in the smart load reduces and thereby causing a momentary rise in Non-critical load voltage as highlighted at t=0.7sec in Fig. 8. Decrease in net resistance of the smart load leads to more real power available in the line setting-off a sudden rise in the line voltage. With an adaptive PI controller of ES, this dynamic condition is restored to normal in 0.1seconds.

Initiation of Voltage Swell

If the generated power by the intermittent source is higher that the load demand, leading to an over-voltage condition. This over-voltage is simulated from 1.5 sec to 2 sec, as shown in Fig. 5. This initiates ES to operate in voltage reduction mode as presented in Fig. 6. Voltage across ES is decreased by 40volts to restore the line voltage back to its nominal value of 220 Volts. ES maintains the voltage across critical load constant in voltage suppression mode by injecting real power and absorbing reactive power into the system as shown in Fig. 7. ES operated with adaptive controller takes 0.1sec that is less when compared with 0.13seconds required by conventional PI controller.

Removal of load under voltage swell condition

When Non-critical load is turned-Off at instant E, the net resistance in the smart load increases and thereby causing voltage appearing across Non-critical load to reduce momentarily at t=1.7sec in Fig. 8. Increase in net resistance of the smart load, makes the circuit less inductive. Thus, the load draws more reactive power from the line causing a dip in the line voltage. Adaptive PI controller of ES senses the under-voltage and generates PWM signals to restore in 0.09seconds.

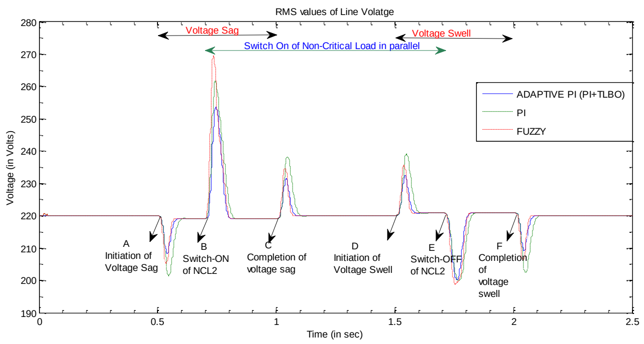


Fig.4. Performance analysis of voltage regulation by PI, Fuzzy and Adaptive PI controllers

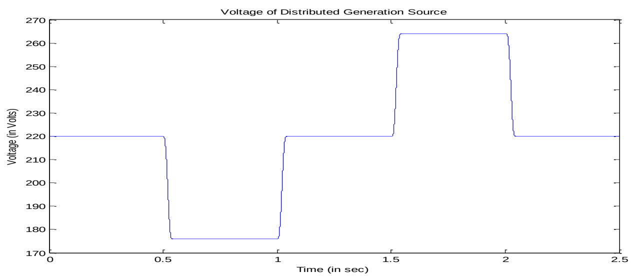


Fig. 5. Line Voltage

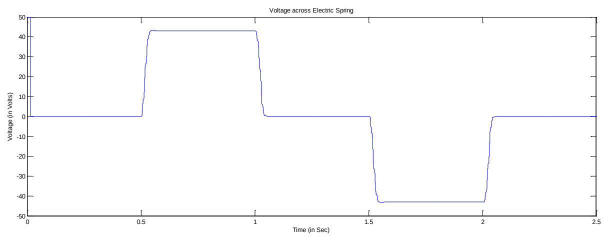


Fig. 6. Voltage across ES

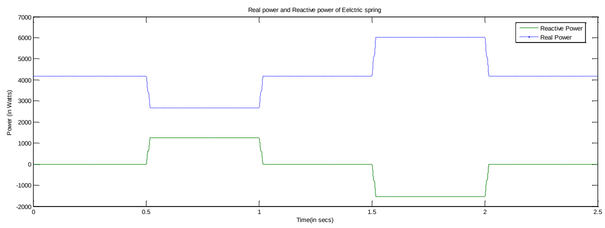


Fig. 7. Real and reactive power across ES

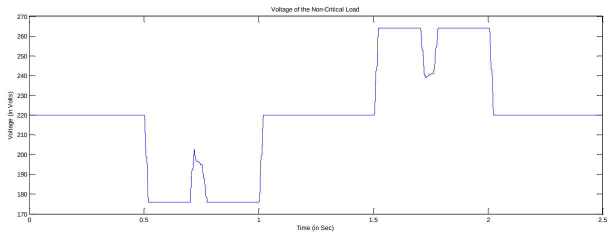


Fig. 8. Voltage across non-critical load

B. Comparison of ES with Adaptive PI controller, PI and Fuzzy Logic Controllers

Fig. 9 and Fig. 10 summarize efficacy of proposed controller over conventional PI and Fuzzy Logic for voltage fluctuations caused by intermittent power sources and dynamic load conditions. This is explained in terms of the maximum allowed voltage variation and setting time of the controller. The solid line in green representing the performance of ES with Adaptive PI controller highlights the fast and better voltage regulation achieved under various operating conditions.

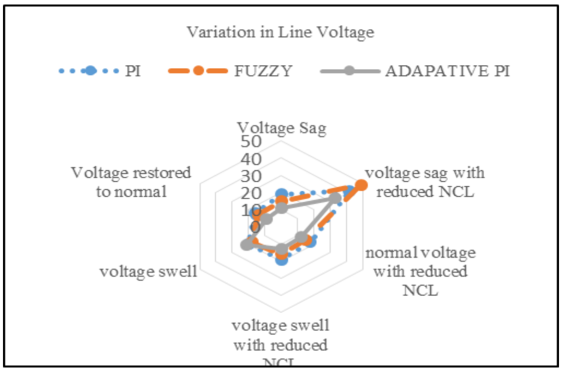


Fig. 9. Voltage Regulation by ES with PI, Fuzzy Logic and Adaptive PI controllers for various operating conditions

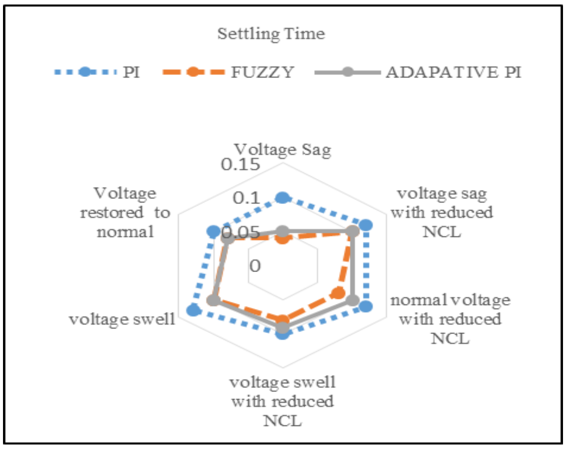


Fig. 10. Comparison Of Performance Of ES With PI, Fuzzy Logic And Adaptive PI Controllers For Various Operating Conditions In Terms Of Restoration Time

V. CONCLUSION

Renewable energy sources cause voltage fluctuations and providing voltage support in such weakly regulated grids is one of the major concerns. Electric Springs facilitates a solution following the phenomenon of Demand side management. Encouraged by the heuristic algorithms in reducing the burden of computations involved in the tuning of a PI controller and TLBO

algorithm has been successfully implemented in the design of parameters of controller of Electric Springs. The usefulness of the adaptive controller has been extensively explained and illustrated with the varying voltage of DG source and dynamic load changes in smart load. Simulation results show that the performance of adaptive controller is faster compared to that of several previously developed traditional PI control and Fuzzy logic Control. Therefore, TLBO can be considered to be a strong tool for obtaining best values of controller gains.

REFERENCES

1. Cheng M, Wang QS, Zhag JZ. Theoretical analysis and controller design of electric springs. Proceedings CSEE 2015;35(10):2436–44.
2. K. Lee, S. C. Tan, F. F. Wu, S. Y. R. Hui, and B. Chaudhuri, "Use of hooke's law for stabilizing future smart grid - the electric spring concept," IEEE Energy Conversion Congress and Exposition, September 2013, pp. 5253–5257.
3. Chen, Yixi & Ma, Gang & Wang, Ying & Xu, Guchao, "An adaptive voltage-regulation control strategy of an electric spring based on output current feedback: Adaptive Voltage-Regulation Control Strategy of Electric Spring", IEE Journal Transactions on Electrical and Electronic Engineering, 2018.
4. Chen, Yixi & Ma, Gang & Xu, Guchao & Chen, Huaiyi & Zhang, Hang. (2018). Restraining the Demand Side Power Fluctuation of Active Distribution Network Using 0 ° / 180 ° Phase Controlled Electric Spring. Journal of Electrical and Computer Engineering. 2018.
5. Akhtar, Zohaib & Alavi, Seyed Amir & Mehran, Kamyar. (2018). Voltage Control in LV Networks Using Electric Springs with Coordination.
6. M. H. T. Omar, W. M. Ali, M. Z. Mostafa," Auto Tuning of PID Controller Using Swarm Intelligence", International Review of Automatic Control (I.RE.A.CO.), Vol. 4, N. 3 May 2011.
7. Nayak, M., Kasturi, K., Rout, P., Optimal Placement and Sizing of Multiple Capacitors in Radial Distribution Systems Using Modified TLBO Algorithm, (2013) International Review of Automatic Control (IREACO), 6 (6), pp. 701-713.
8. Taki El-Deen, A., Mahmoud, A., R. El-Sawi, A., Optimal PID Tuning for DC Motor Speed Controller Based on Genetic Algorithm, (2015) International Review of Automatic Control (IREACO), 8 (1), pp. 80-85.doi:https://doi.org/10.15866/ireaco.v8i1.4839.
9. Sadek, M., Elkholy, M., Metwally, H., Efficient Operation of Wind Turbine with Doubly Fed Induction Generator Using TLBO Algorithm and Artificial Neural Networks, (2016) International Review on Modelling and Simulations (IREMOS), 9 (6), pp. 464-472. doi:https://doi.org/10.15866/iremos.v9i6.10309.
10. S. Yan, S. C. Tan, C. K. Lee, and S. Y. R. Hui, "Electric spring for power quality improvement," in Proc. IEEE APEC, 2014, pp. 2140–2147.
11. K. Lee and S. Y. .Hui, "Reduction of energy storage requirements in future smart grid using electric springs," IEEE Transactions on Smart Grid, vol. 4, no. 3, pp. 1282–1288, Sept 2013.
12. Y. Shuo, S. C. Tan, C. K. Lee, and S. Y. R. Hui, "Electric spring for power quality improvement," in 2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014, March 2014, pp. 2140–2147.
13. Lee CK, Chaudhuri B, Hui SYR. Hardware and control implementation of electric springs for stabilizing future smart grid with intermittent renewable energy sources. IEEE Journal of Emerging Sel Top Power Electronics 2013.
14. R.V. Rao, V.J. Savsani, D.P. Vakharia, "Teaching–learning-based optimization: A novel method for constrained mechanical design optimization problems", Computer-Aided Design 43 (2011) 303–315.
15. S. C. Tan, C. K. Lee, and S. Y. Hui, "General steady-state analysis and control principle of electric springs with active and reactive power compensations," IEEE Transactions on Power Electronics, vol. 28, no. 8, pp. 3958–3969, Aug 2013.

AUTHORS PROFILE

K.K.Deepika received her B.Tech. degree in Electrical and Electronics Engineering from Bapatla Engineering College, Guntur. She received her M.Tech. degree in Power Systems and Automation from GITAM University. She is currently pursuing her Ph. D. degree in Electrical Engineering at KLEF, Vijayawada, Andhra Pradesh, India.
Her research interests include Distribution Systems, Renewable energy Sources and reactive power control. Ms. Deepika is a member of IEEE, IEI (I) and IAENG.

Dr. J.Vijaya Kumar received B. Tech. from J. N. T. U Kakinada in 2002, M.Tech. from Maulana Azad National Institute of Technology (MANIT) Bhopal in 2005 and Ph.D. degree in Electrical Engineering from National Institute of Technology (NIT), Warangal.
His current research interests include power system deregulation and artificial intelligence technique applications in power systems. He has 2 publications in SCI journals and 4 in Scopus indexed international journals.

Prof. G.Kesava Rao received his Ph. D. degree in Electrical Engineering from IIT Varnasi, India. His research interests include Distribution Systems, Phasor Measurement Units and Electric vehicles.

Seelam Chaitanya received her B.Tech. degree in Electrical and Electronics Engineering from Vignan's Institute of Engineering for Women, Visakhapatnam. She received her M.Tech. degree in Power and Industrial Drives from Vignan's Institute of Information Technology, Visakhapatnam.