Recapitulation of Electric Spring: A Smart Grid Device for Real Time Demand Side Management and Mitigating Power Quality Issues

Mehul Dansinh Solanki
Electrical Engineering Department
Shantilal Shah Engineering College
Bhavnagar, Gujarat, India
Email: solankimehuld@gmail.com

S. K. Joshi
Electrical Engineering Department
The Maharaja Sayajirao University of Baroda
Vadodara, Gujarat, India
Email: skjoshi@ieee.org

***Abstract*—Review of theory, application, modelling, and limitations of an electric spring (ES), a custom power device, is provided after going through published literature in this field. An ES controls active as well as reactive power and hence can regulate voltage along with power quality enhancement, in the presence of intermittent and unpredictable renewable energy sources. ES is connected in series with part of the total load and can damp out the oscillations of the grid by providing voltage regulation to the load and acts as a smart load. Presence of numerous ES can be visualized in a distribution feeder, acting simultaneously in unison without having any communication within.**

***Index Terms*—Custom power devices, demand side management, Flexible AC Transmission System (FACTS), smart grid, voltage stability**

I. Introduction

Rising concern over environmental issues and carbon emission by the world community has left with us no choice but to switch over to clean energy alternatives having less or no emissions, as majority of todays power generation is available through thermal power stations. Renewable energy sources (viz. wind and solar based power generation) offers clean energy but are of intermittent in nature and its availability is unpredictable with least forecasting accuracy. Few of the nations like India agreed upon to increase the penetration of renewable energy sources up to 20%, [1],[2],[3] by the year 2020. Greater penetration of these renewable energy sources in the main grid or in distribution system causes serious stability issues [4],[5],[6] and hence it has to be addressed with great care.

Stability issues of intermittent and unpredictable nature of renewable energy sources can only be addressed by resorting to some means of load management rather than generation management. Demand Side Management (DSM), also called demand dispatch, [7] is one such alternative and numerous methods of DSM [8],[9] have been studied in the past three decades. All these Demand Side Management techniques either resort to some method of peak load shaving or by incorporating some or the other means of energy storage. Real time prizing [10],[11],[12], scheduling [13],[14],[15] or on–off control [16],[17] of delay tolerant load viz. washing machines are few such mechanisms which offers Demand Side Management through load shaving. Battery storage happens to be the most effective method of Demand Side Management [18] which offers balancing of the load demand but it is very costly and having limited life span. Disposal of the same is again causing serious environmental issues. All these methods of Demand Side Management can only be implemented by relying on to some means of information and communication technologies (ICT). Internet of Things (IoT) [19] is another such mechanism to manage electrical loads remotely and smartly based on a specific tariff condition, or when power demanded by of the system

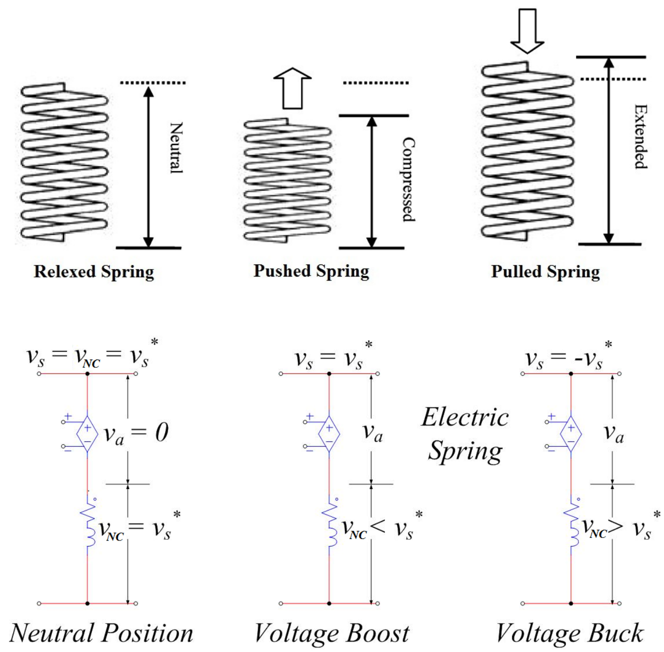

Fig. 1. Analogy of Mechanical spring and ES [22].

978-1-4799-5141-3/14/$31.00 © 2016 IEEE

is very low. These all technologies come with an extra cost to be paid in terms of latency in signal traversal and risk of hacking. It hampers the freedom of energy usage by the end user in the real time bases and is bit intrusive in nature.

Electric spring can offer Demand Side Management in the real time basis without resorting to the ICT and hence need no ramification to the issues associated with ICT. Electric spring has been established on the profound theory of the Hooks law [20] explaining the behavior for mechanical spring and hence named so. Working analogy of the two can be depicted form Fig. 1.

Concept of electric spring was originally introduced in [21] without load bifurcation and later established as electric spring by S. Y. R. Hui et.al. [22]. Electric spring is a custom power device [23] connected in between load and intermittent source. Load can be classified on the basis of its tolerable voltage range, and further named as critical and noncritical load. Major chunk of the total load of any distribution system is of HVDC, heating and cooling type (dissipative in nature) of load and can tolerate wide voltage variation so is designated as noncritical load. Category of critical load is occupied by data centers, critical hospital/surgical facilities and central monitoring and control facilities which happen to be the least tolerant to the voltage variation. Energy consumption of large residential societies and commercial load viz. Hotels [24] are ideal contenders to such load bifurcation where almost 70% [25] of the total load is of dissipative in nature and hence forms noncritical load, rest of the load can be considered as critical load. Critical load is connected across the series combination of electric spring and noncritical load and together this combination is forming smart load. We can think of multiple electric springs dispersed throughout in the distribution system, acting in tandem without any communication in-between and can source or sink active or reactive power so as to provide voltage regulation and ultimately grid stability.

II. Construction And Working

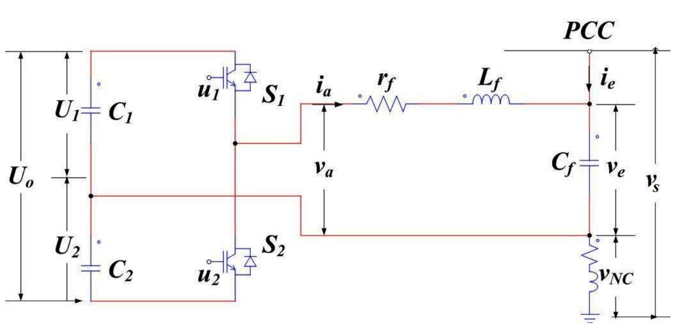

Fig. 2. ES performing as smart load [26].

An electric spring is a custom power device (Fig. 2), i.e. a power electronic converter which can be either three phase or single phase type as per the demand of the load, and is connected in series with noncritical load, operating with input feedback and output voltage control [22]. An electric spring can also be represented as current controlled voltage source. Classification of electric spring can be made on the basis of the source of DC voltage available at the DC bus and is as follows:

1) Ist generation electric spring: A capacitor is connected on DC bus [22]
2) IInd generation electric spring: A battery is connected on DC bus [35].
3) IIIrd generation electric spring: A bidirectional power electronic converter of appropriate type and of an appropriate configuration is connected on DC bus [35].

Ist generation Electric Spring can manage to feed in or absorb reactive power only and can operate in any of the following two modes:

1) Inductive mode: absorbing reactive power (v_e is lagging behind ie by 90^o) by suppressing line voltage (Fig. 3 (a)).
2) Capacitive mode: injecting reactive power (v_e is leading ie by 90^o) so as to enhance the line voltage (Fig. 3 (b)).

IInd gen. and IIIrd gen. electric spring can source or sink active as well as reactive power by controlling the injected voltage over 0^o to 360^o with respect to ie. Six more modes can be derived for this operation as:

1) Positively resistive: ES draws active power (angle between v_e and i_e is 0^o) by sinking power (Fig. 3 (c)).
2) Negatively resistive mode: ES is sourcing real power (angle between v_e and i_e is 180^o) (Fig. 3 (d)). Combination of above four modes further gives out four more modes:
3) Positively Resistive + inductive mode (Fig. 3 (e)).
4) Negatively Resistive + inductive mode (Fig. 3 (f)).
5) Positively Resistive + capacitive mode (Fig. 3 (g)).
6) Negatively Resistive + capacitive mode (Fig. 3 (h)).

Control of these electric springs can be devised in such a manner that when load current and injecting voltage by electric spring is at quadrature, can source or sink reactive power only and any other angle in between can handle active power along with reactive power. Injection of voltage by electric spring changes the voltage of noncritical load and hence its power flow. Algebraic summation of voltage of ES and noncritical load gives the voltage to be available across the critical load. This is how the voltage profile of critical load is maintained constant by modulating the power of noncritical load, and hence providing voltage stability [27] to the grid. It is doing so in a manner similar to a mechanical spring and hence justifying its name, and commensurating with requirements of demand side management so as to achieve risk limiting dispatch [28],[29].

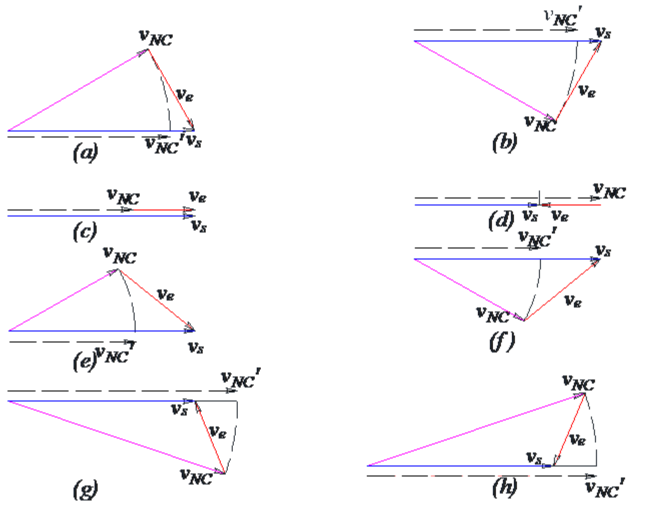

Fig. 3. Phasor representation of various modes: (a) Inductive (b) Capacitive (c) Resistive (d) Negatively Resistive (e) Resistive+inductive (f) Resistive+Capacitive (g) Negatively Resistive+ inductive (h) Negatively Resistive+Capacitive [30].

Vector explaining these eight operating modes can be found in Fig. 3 and steady state power analysis of electric spring operating in these eight modes can be found in [31], along with its control mechanism. It has been established through mathematical analysis that an electric spring can provide voltage regulation, power quality enhancement and frequency stabilization through real power control in the presence of intermittent renewable energy sources, and same has experimentally been verified.

III. Modelling of Electric Spring

Model of any system provides detailed mathematical insight to that system and further it says a lot about stability of the system incorporated with an appropriate control. All power electronic converters are nonlinear in nature and hence it has to be linearized so as to implement some linear control mechanism [32]. Modelling can be started with exact or switched model and further through suitable assumptions one can derive generalized averaged model in state–space [33] form. Dynamic average model of electric spring for the circuit shown in Fig. 2 is derived in [34] as:

$\dot{X} = A.X + B.e$

Where, $X = [i_a \ v_e]^T$, u =switching function of converter switches and, A, B and e are as follows:

$$A = \begin{bmatrix} -\frac{r_f}{L_f} & -\frac{1}{L_f} \\ \frac{1}{C_f} & -\frac{1}{R_{NC}\times C_f} \end{bmatrix}, B = \begin{bmatrix} \frac{1}{2L_f} \\ \frac{1}{R_{NC}\times C_f} \end{bmatrix}, e = \begin{bmatrix} uU_0 \\ v_s \end{bmatrix}$$

Dynamics of capacitor at DC bus has been neglected for the sake of simplicity and ease in deriving this state space model without loss of significant accuracy.

IV. Control of Electric Spring

Performance of any distribution system can be counted on stability and power quality indices, as it defines the comfort and satisfactory usage of electricity by the end user. Quality of the power refers to well regulated i.e. constant voltage, balanced phases, unity power factor, constant frequency and absolutely sinusoidal voltage and current profile.

Electric spring found to have been working satisfactorily in all the eight operating modes explained in section II. Control block for the same can be found in [43]. It has been proved in [35] that active power can also be handled by replacing capacitor with a battery and its size required 50%, of that required for active power management in a conventional system. Few more functionalities emerged out of the active research in the area of electric spring and is explained below.

Being a shunt connected controller, an electric spring can easily made to work as shunt active power filter [36],[37],[38],[39],[40],[41],[42] so as to mitigate harmonics generated by critical load. Same has been studied in [43]. It reduces harmonics as per the recommendations of IEEE–519 [44]. It can also made to work for power factor correction [30], voltage balancing [45] and reduction of neutral current [46] and frequency control in a micro–grid [47]. These all the point leads to enhance the power quality along with electric springs conventional responsibility of improvising voltage profile. One such device incorporating all these functionalities has already been investigated as shunt active power filter in [48]

V. Control Of Dispersed Electric Springs

Drooping voltage profile can be seen along the feeder length, if we start traversing from substation to the tail end, due to feeder impedance and load tapping. This causes the voltage level to be differed and diminishing at every point of the feeder and it is least at the tail end. Droop control of feeder is not a new concept and has been presented in numerous papers for generators [49],[50] and grid connected inverters [51] working in parallel. We can implement this concept for the control of electric springs, dispersed along the length of the feeder.

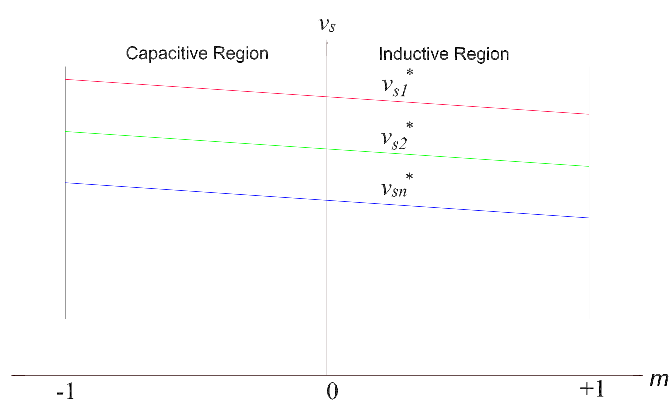

Fig. 4. Characteristic of ES dispersed along distribution feeder.

If we set the same voltage reference for the control of all such electric springs, then each spring tries to get that reference and that makes them to work in different mode. Electric spring placed near the sending end will have the highest voltage and hence will work in inductive mode while the spring near the tail end will work in the capacitive region of operation. Setting the same voltage reference will not allow them to work in unison. To avoid this situation, droop control of parallely distributed electric springs have been proposed [52], where in voltage reference ($v_{s1}^*, v_{s2}^*, v_{s3}^*, v_{sn}^*$) of each electric spring is automatically adjusted so as to follow the drooping profile of the feeder and the same can be verified from Fig. 4. Rating of such droop controlled electric springs have been found less as that compared to the implementation of parallel connected electric springs having no droop control. The control of such multiple springs does not demand for central control and any communication network for following the drooping profile of the voltage.

It has been verified that no communication network is made available between all such dispersed electric springs and yet all are acting in tandem to serve the cause and with much a less rating.

VI. Electric Spring Verses FACTS

FACTS and custom power devices share many common things. Power electronic converter is acting as a key component for both the group of devices. They work for power quality enhancement and real and reactive power support.
We can distinguish FACTS and electric spring with following arguments:

1) Almost all FACTS [53] devices are meant to work with transmission system except the few viz. D–STATCOM and they are point sources of compensation and possesses very high ratings and cost whereas an electric spring is acting as an integral part of the load having been dispersed throughout the distribution feeder, possesses low cost due to smaller ratings [54].
2) An electric spring can compensate for active as well as reactive power whereas a FACTS controller is meant for reactive power [55],[56],[57] control only.
3) Electric spring is an input voltage controller rather than the conventional output voltage control [56] in the case of tra,ditional FACTS controllers.
4) Electric spring is a current controlled voltage source, whereas FACTS devices are voltage controlled voltage source[57].

VII. Operating Limits Of Electric Spring

Elastic limit confines the operation of mechanical spring in specific bounds and beyond which its operation is creating fatigue or can damage the mechanical spring. Likewise, operation of electric spring is limited by the proportion of critical and noncritical load, and voltage of the DC bus.

Being a power electronic converter, operation of an electric spring is governed by voltage delivered by capacitor on the DC bus. By increasing the injection of voltage from electric spring, voltage across the noncritical load is decreased, further decreasing the power to be consumed by the noncritical load and vice avers. Modulation of power in noncritical load is limited by its tolerable range of operating voltage. This further imposes a limit on the operation of electric spring in terms of voltage regulation and reactive power compensation. Vector diagram (Fig. 5) [46] exhibits the same phenomena. Capacitor voltage U_o is driving the voltage injected by electric spring which it can control in the range of 0^o to 360^o with respect to v_s. all the hatched lines show expected values and solid lines exhibit prevailing parameters in electric spring. Noncritical load current i_e takes on solid yellow line and represents operating limits as explained earlier. This is how line current takes on solid blue line (rather than dashed line) and causes deviation in the angle which deteriorates the performance of electric spring due to poor power factor. It is evident from the ongoing discussion that operational voltage range of noncritical load is crucial in the design and performance of electric spring.

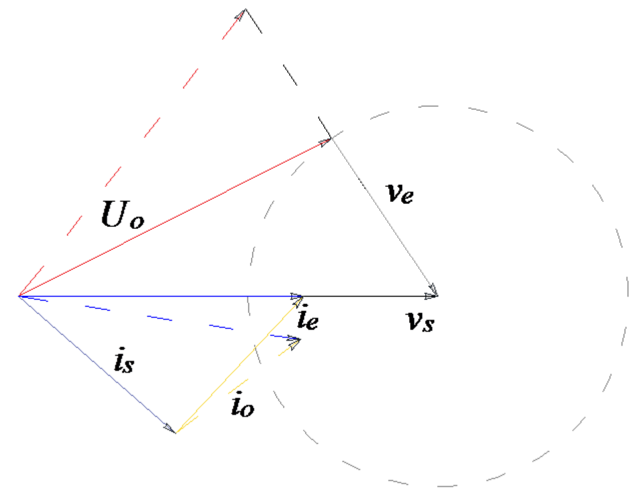

Fig. 5. Operational limits of electric spring [46]

In the case of Ist generation electric spring, proportion of critical and noncritical load (C:NC) further poses limitation on the voltage regulation and reactive power compensation and same has been investigated in [34]. Proportion C:NC = 1:9 offers excellent voltage regulation and hence reactive power compensation, as that compared to C:NC = 1:1 is the weakest one. If we further increase the share of critical load by 90%, and electric spring is not there in the position to serve its duty as a good voltage regulator and a reactive power compensator. This can easily be taken care by resorting to second or third generation of electric spring.

VIII. Conclusion

We are rapidly marching towards greater integration of renewable energy resources in the main grid or in the distribution system, due to our environmental concern. Availability of power from these distributed generators is intermittent and unpredictable and hence creating issues related to stability. Electric spring is a custom power device which can address the issue of stability by injecting voltage in series with noncritical load so as to modulate noncritical load power along the generation pattern of intermittent source and together this combination is regulating the voltage of critical load voltage constant, which makes the load even smarter. It does this by changing the angle of injected voltage such that it can sink or source the active or reactive power. An electric spring can also handle the power quality issues like balance of voltage, reducing neutral current, mitigating harmonics, frequency control, and power factor correction along with its fundamental responsibility of voltage regulation. It made the load to act as smart load as it maintains the voltage of load which badly needs this (critical load), at the cost of modulation of noncritical load as per the profile of intermittent source as it can easily tolerate voltage variation. Electric spring requires very small battery storage for active power management. Multiple electric springs can be incorporated in a distribution system implemented with droop control without any mode of communication and this makes a distribution system smarter in terms of voltage regulation and active and reactive power management. It is cheaper than distribution FACTS controller due to smaller rating. In a way it is commensurating with the requirements of demand side management that too in the real time basis. Modeling, analysis and control aspects of electric spring are reviewed form the available published literature.

REFERENCES

[1] Vision 2020 Sustainability of India's Material Resources, [Online] Available: http://planningcommission.nic.in/reports/genrep/bkpap2020/13_bg2020.pdf

[2] Meeting the energy challenge: A white paper on energy, May 2007 [Online] Available: http://webarchive.nationalarchives.gov.uk/20090609003228/http://www.berr.gov.uk/files/file39387.pdf

[3] On investing in the development of low carbon technologies (SETplan) a technology roadmap, Commission of the European Communities, Brussels, Belgium, 2009.

[4] Math Bollen, The Smart Grid - Adapting the power system to new challenges, Synthesis Lecturers on Power Electronics, Series Editor: Jerry Hudgins, Morgan & Claypool Publishers, Chapter 2, 2011

[5] M. J. Hossain, Hemanshu R. Pota, Md. Apel Mahmud, and Rodrigo A. Ramos, Investigation of the Impacts of Large–Scale Wind Power Penetration on the Angle and Voltage Stability of Power Systems, *IEEE Systems journal*, vol. 6, no. 1, pp. 76–84, March. 2012.

[6] A. M. Azmy and I. Erlich, Impact of distributed generation on the stability of electrical power system, *in Proc. 2005 IEEE Power Eng. Soc. Gen. Meeting*, vol. 2. San Francisco, CA, USA, pp. 10561063.

[7] A. Brooks, E. Lu, D. Reicher, C. Spirakis, and B. Weihl, Demand dispatch, *IEEE Power Energy Mag.*, vol. 8 , no. 3 , pp. 20-29, 2010.

[8] I. Koutsopoulos and L. Tassiulas, Challenges in demand load control for the smart grid, *IEEE Netw.*, vol. 25, no. 5, pp. 16-21, 2011.

[9] P. Palensky and D. Dietrich, Demand side management: Demand response, intelligent energy systems, and smart loads,*IEEE Trans. Ind. Inform.*, vol. 7, no. 3, pp. 381-388, 2011.

[10] A. J. Roscoe and G. Ault, Supporting high penetrations of renewable generation via implementation of real-time electricity pricing and demand response, *IET Renewable Power Generation*, Volume: 4 , Issue: 4, 2010 , pp. 369 - 382

[11] A. J. Conejo, J. M. Morales and L. Baringo, Real–Time Demand Response Model, *IEEE Transactions on Smart Grid*, Volume: 1, Issue: 3, 2010, pp. (s): 236-242

[12] A. H. Mohsenian Rad and A. Leon Garcia,; Optimal Residential Load Control With Price Prediction in Real-Time Electricity Pricing Environments, *IEEE Transactions on Smart Grid*, Volume: 1 , Issue: 2, 2010 , pp. 120133

[13] M. Pedrasa, T. D. Spooner, and I. F. MacGill, Scheduling of demand side resources using binary particle swarm optimization, *IEEE Trans. Power Syst.*, vol. 24, no. 3 , pp. 1173-1181, 2009.

[14] L. Garcia, Autonomous demand–side management based on gametheoretic energy consumption scheduling for the future smart grid, *IEEE Trans. Smart Grid*, vol. 1 , no. 3 , pp. 320-331, 2011.

[15] M. Parvania and M. F. Firuzabad, Demand response scheduling by stochastic SCUC, *IEEE Trans. Smart Grid*, vol. 1, no. 1, pp. 89-98, 2010.

[16] S. C. Lee, S. J. Kim, and S. H. Kim, Demand side management with air conditioner loads based on the queuing system model, *IEEE Trans.Power Syst.*, vol. 26, no. 2 , pp. 661-668, 2011.

[17] G. C. Heffner, C. A. Goldman, and M. M. Moezzi, Innovative approaches to verifying demand response of water heater load control, *IEEE Trans. Power Del.*, vol. 21, no. 1 , pp. 388-397, 2006.

[18] F. Kienzle, P. Ahcin, and G. Andersson, Valuing investments in multi-energy conversion, storage, and demand-side management systems under uncertainty, *IEEE Trans. Sustainable Energy*, vol. 2, no. 2, pp. 194-202, Apr. 2011

[19] Ovidiu Vermisen, Peter Fries, Internet of Things– From Research and Development to Market Deployement, River Publisher Series in Communication, Chapter–3, 2014

[20] Hookes lawBritannica Encyclopedia [Online]. Available: http://www.britannica.com/EBchecked/topic/271336/Hookes–law

[21] S. Dasgupta, S. K. Sahoo, S. K. Panda and G. A. J. Amaratunga, "Single–Phase Inverter–Control Techniques for Interfacing Renewable Energy Sources With Microgrid-Part II: Series–Connected Inverter Topology to Mitigate Voltage–Related Problems Along With Active Power Flow Control," *IEEE Transactions on Power Electronics*, vol. 26, no. 3, pp. 732–746, 2011.

[22] S. Y. R. Hui, C. K. Lee and F. F. Wu, Electric springs - A new smart grid technology, *IEEE Transactions on Smart Grid*, Vol. 3, No. 3, pp. 1552–1561,Sept. 2012.

[23] Arindam Ghosh, Gerard Ledwich, *Power Quality Enhancement Using Custom Power Devices*, Kluwer Academic Publishers, 2002

[24] U. S. Department of Energy Commercial Reference Building Models of the National Building Stock, Technical Report, NREL TP-550046861, Feb. 2011.

[25] L. P. Lombard, J. Ortiz, and C. Pout, A review on buildings energy consumption information, *Energy and Buildings*, Mar. 2007.

[26] Mehul Dansinh Solanki and S. K. Joshi, Review of Electric Spring: A New Smart Grid Device for Efficient Demand Dispatch and Active and Reactive Power Control, *2016 Clemson University Power Systems Conference (PSC), Clemson, SC*, pp. 1-8, Mar. 2016.

[27] C. K. Lee, B. Chaudhuri, and S. Y. R. Hui, Hardware and control implementation of electric springs for stabilizing future smart grid with intermittent renewable energy sources, *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 1, pp. 18-27, 2013.

[28] P. Varaiya, Felix F. Wu and Janusz W. Bialek, Smart Operation of Smart Grid: Risk-Limiting Dispatch, *in proc.IEEE*, VOL. 99, Issue: 1, pp. 40-57, Jan. 2011.

[29] Rajagopal, R., Bitar, E., Wu, F., Varaiya, P., Risk Limiting Dispatch of Wind Power, *American Control Conference*, Montral, Canada, Jun. 2012.

[30] S. Yan, S. C. Tan, C. K. Lee, S. Y. R. Hui, Electric spring for power quality improvement, *in Proc. of 29th IEEE Applied Power Electronics Conference and Exposition*, pp. 2140-2147, 2014.

[31] S. C. Tan, C. K. Lee, and S. Y. R. Hui, General steady–state analysis and control principle of electric springs with active and reactive power compensations, *IEEE Trans. Power Electronics*, vol. 28, no. 8, pp. 3958-3969, 2013.

[32] Rimmalapudi S. R., Williamson S. S., Nasiri A, Emadi A, Validation of generalized state space averaging method for modeling and simulation of power electronic converters for renewable energy systems, *J Electr Eng Technology*, vol. 2(2), pp. 231-240

[33] S. R. Sanders, J. M. Noworoloski, X. Z. Liu and G. C. Verghese, Generalized averaging method for power conversion circuits, *IEEE Trans. On Power Electronics*, vol. 6, no. 2, pp. 251-289, 1991.

[34] N. R. Chaudhuri, C. K. Lee, B. Chaudhuri and S. Y. R. Hui, Dynamic Modeling of Electric Springs, *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2450-2458, 2014.

[35] C. K. Lee and S. Y. R. Hui, Reduction of energy storage requirements for smart grid using electric springs, *IEEE Transactions on Smart Grid*, VOL. 4, NO. 3, pp. 1282-1288, SEPT. 2013.

[36] M. D. Solanki and S. K. Joshi, Mitigation of harmonics through shunt active filter based on PI regulator with anti windup integral action, *in Conf. Proc. 22nd AUPEC–2012*, pp. 1-6, Oct. 2012.

[37] B. Singh, K. Al-Haddad, and A. Chandra, A review of active filters for power quality improvement, *IEEE Trans. on Ind. Electron.*, vol. 46, no. 5, pp. 960-971, Oct. 1999.

[38] C. C. Chen and Y. Y. Hsu, A novel approach to the design of a shunt active filter for an unbalanced three-phase four-wire system under nonsinusoidal conditions, *IEEE Trans. Power Delivery*, vol. 15, no. 4, pp. 1258-1264, Oct. 2000.

[39] J. W. Dixon, J. J. Garcia, and L. Moran, Control system for three-phase active power filter which simultaneously compensates power factor and unbalanced loads, *IEEE Trans. Ind. Electron.*, vol. 42, no. 6, pp. 636-641, Dec. 1995.

[40] P. Verdelho and G. D. Marques, An active power filter and unbalanced current compensator, *IEEE Trans. on Ind. Electron.*, vol. 44, no. 3, pp. 321-328, Jun. 1997.

[41] S. George and V. Agarwal, A DSP based optimal algorithm for shunt active filter under nonsinusoidal supply and unbalanced load conditions, and smart loads, *IEEE Trans. on Power Electron.*, vol. 22, no. 2, pp. 593-601, Mar. 2007.

[42] V. B. Bhavaraju and P. N. Enjeti, Analysis and design of an active power filter for balancing unbalanced loads, *IEEE Trans. Power Electron.*,vol. 8, no. 4, pp. 640–647, Oct. 1993.

[43] P. Kanjiya, and V. Khadkikar, Enhancing power quality and stability of future smart grid with intermittent renewable energy sources using electric springs, *International Conference on Renewable Energy Research and Applications.*, pp. 918-922, 2013.

[44] IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems, IEEE Standard 519, 2014.

[45] A. von Jouanne and B. Banerjee, Assessment of voltage unbalance, *IEEE Trans. Power Delivery*, vol. 16, no. 4, pp. 782-790, Oct. 2001.

[46] S. Yan, S. C. Tan, C. K. Lee, and S. Y. R. Hui, Reducing Three–Phase Power Imbalance with Electric Springs, *IEEE 5th International Symposium on Electronics for Distributed Generation Systems (PEDG)*, pp. 1-7, 2014.

[47] Xia Chen, Yunhe Hou, Siew–Chong Tan, C. K. Lee, and S. Y. R. Hui, Mitigating Voltage and Frequency Fluctuation in Microgrids Using Electric Springs, *IEEE Transactions on Smart Grid* (early access).

[48] A. Chandra, B. Singh, B. N. Singh, and K. Al–Haddad, An improved control algorithm of shunt active filter for voltage regulation, harmonic elimination, power-factor correction, and balancing of nonlinear loads, *IEEE Trans. Power Electron.*, vol. 15, no. 3, pp. 495-506, May 2000.

[49] J. Machowski, J. Bialek, and J. Bumby, *Power System Dynamics and Stability*, New York, NY, USA: Wiley, 1997, pp. 21-25.

[50] B. W. Weedy and B. J. Cory, *Electric Power Systems*, 4th ed., 1998, New York, NY, USA: Wiley.

[51] K. De Brabandere et.al., A voltage and frequency droop control method for parallel inverters, *IEEE Trans. Power Electron.*, vol. 22, no. 4, pp.1107-1115, Jul. 2007.

[52] C. K. Lee, N. Chaudhuri, B. Chaudhuri and S. Y. R. Hui, Droop Control of Electric Springs for Distributed Stability Support of Smart Grid, *IEEE Transactions on Smart Grid*, VOL. 4, NO. 3, pp. 1558-1566, 2013.

[53] Juan Dixon, Luis Morn, Jos Rodrguez, Ricardo Domke, Reactive Power Compensation Technologies: State–of–the–Art Review, *in proc. IEEE*, Vol. 93, No. 12, Dec. 2005

[54] X. Che, T. Wei, Q. Huo, and D. Jia, A General Comparative Analysis of Static Synchronous Compensator and Electric Spring, *ITEC Asia-Pacific*, pp. 1-5, 2014.

[55] P. Sauer, Reactive power and voltage control issues in electric power systems, Appl. Math. Restructured Elect. Power Syst. pp. 11–24, 2005.

[56] Y. Rong, C. Li, H. Tang and X. Zheng, Output feedback control of single–phase UPQC based on a novel model, *IEEE Transactions on Power Delivery*. vol. 24. pp. 1586–1597, July 2009.

[57] H. Fujita, Y. Watanabe and H. Akagi, Control and analysis of a unified powerflow controller, *IEEE Trans. Power Electronics*, vol. 14, pp. 1021–1027, 1999.