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A Survey and Comparative Evaluation of FACTS Controllers in Power System Performance Enhancement

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Abstract**—** The demand for electricity has increased significantly in recent years, and the expansion of power transmission and distribution networks has been severely limited due to resource and environmental constraints. This has resulted in some transmission lines being overloaded and hence increase in system instability. Developed in the last decades of the last century, Flexible AC Transmission Systems (FACTS) controllers have become one of the most prominent solutions for optimizing the electricity grid. FACTS controllers can control the active and reactive power flows within a transmission line by controlling the shunt and series parameters of the transmission line. Due to their flexibility, different types of FACTS controllers have been proposed to solve different operating problems in power systems and are well recognized for their technical advantages, but high cost is one of the factors that limit the spread of this technology. This paper presents an exhaustive survey of various types of FACTS devices and the problem(s) they can solve to enhance power system performance. Also, cost comparison of various FACTS controllers is presented in this study. The objective of the study is for the paper to serve as a guide for selecting the most appropriate FACTS controller to solve a particular power system problem while also considering the cost.

Keywords**—** Active and reactive power, FACTS controllers, Optimal allocation, Power system performance.

I. INTRODUCTION

Flexible AC Transmission System (FACTS) controllers refer to power electronic-based system and other static equipment that control one or more AC transmission system parameters to improve controllability and power transfer capabilities [1]. Its concept was first introduced by N.G Hingorani, in the 1990's [2]. As power transfer grows, the power system becomes increasingly complex to operate. Huge power flows with insufficient control, excessive reactive power in different sections of the network, prolonged dynamic swings between various parts of the network, and other bottlenecks make it hard to fully use the potential of transmission networks [3].

The difficulty to acquire new rights of way has led to greater demands on the transmission networks causing many challenges in the operation of the systems. FACTS controllers are of critical importance for addressing some of these challenges by allowing utilities to get the most from their transmission systems while also improving grid performance [4].

FACTS controllers can provide versatile benefits to power transmission companies, such as control of power flow as required, increase the loading capability of lines to their thermal capabilities, increasing the system security by raising the transient stability limit, providing greater flexibility in siting new generation, limiting overloads and short-circuit currents, minimizing cascading blackouts, damping electromechanical oscillations of power systems, providing secure tie line link to neighbouring utilities and regions thereby reducing the overall generation reserve requirements on both sides, reduce reactive power flows hence enabling the lines to carry more active power, reducing loop flows, and increasing utilization of lowest cost generation [3]. There are already many research works addressing these benefits listed above, and a review of these applications is provided in [5].

Based on the many researches and industrial application of FACTS controllers in recent years, it can be said that this technology has reached maturity and the cost of these power electronics-based controllers has considerably decreased. However, the investment cost of FACTS controllers is still high, therefore, optimal allocation of theses controllers in the Power System is a crucial factor. There are several FACTS controllers' allocation techniques that have been developed in the last years for optimization of power system performance [6].

Despite the numerous technical benefits of FACTS devices, some questions need to be thought about: Will FACTS' devices be profitable in operation? Can we make the best use of FACTS if their technical and their economic values are not both considered? What should investors look at when deciding the scale of their investments on FACTS controllers? Surprisingly, compared to the large body of FACTS' technical aspects, there are only very limited references on the economic aspect of FACTS, and their manner of evaluation needs further discussion.

In this paper, the general concepts of various FACTS devices are briefly discussed and a detailed comparative survey of conventional solutions and FACTS controllers for addressing steady state and dynamic state problems is tabulated. Further, an investment analysis and economic comparison for different FACTS controllers are presented in detail. In conclusion, some possible directions for future research in this field are provided.

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II. CLASSIFICATION OF FACTS DEVICES

FACTS technology is a collection of controllers that can be applied to control a set of inter-related electrical variables and parameters, including voltage, impedance, phase angle, current, reactive and active power [2], providing greater flexibility to the system operation, enhancing the opportunities to perform various functions as pointed out earlier. FACTS controllers are of different types. They are classified according to their connection, namely; shunt connected, series connected, and combined series and shunt connected controllers.

Series Controllers: They are those that are connected to the transmission line in series. They inject voltage and current into the transmission system in series. Its illustrative diagram is shown in Fig.1 [7].

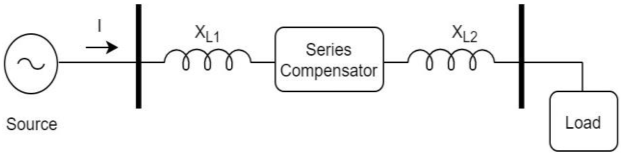

Fig. 1: Schematic of Series FACTS Controller

Shunt Controllers: These controllers are linked to the transmission line in parallel. They inject voltage and current into the transmission system in parallel. Illustratively, the schematic diagram of a shunt controller is shown in Fig.2 [7].

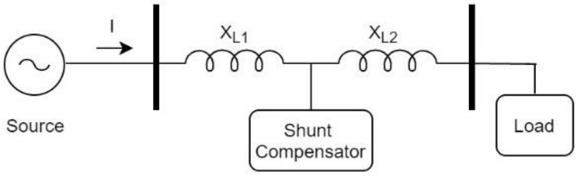

Fig. 2: Schematic of Shunt FACTS Controller

Combined series-shunt controllers: They are those in which a one controller is connected in series and another is connected in parallel and they both are coupled via a coordinated control and a common dc power link in transmission line to transmit the current, voltage and power. Fig.3 shows the combined Series-Shunt controller [8].

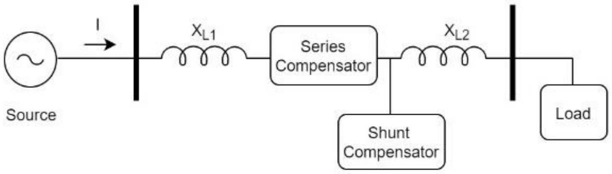

Fig. 3: Schematic of Combined Series-Shunt FACTS Controller

The main and widely used types of FACTS controllers are described below:

A. Static Var Compensators (SVC)

The most common shunt FACTS controller is the SVC, it is not very efficient at solving dynamic voltage problems. In comparison to traditional shunt compensation, SVCs provide high performance steady state and transient voltage regulation due to their high precision and quick reaction. SVCs are also utilized in reactive power control to enhance transient stability, dampen power fluctuations, and decrease system losses [9].

B. Static Synchronous Compensator (STATCOM)

STATCOMs are GTO (gate turn-off type thyristor) based SVCs. To deliver inductive or capacitive reactive power to high voltage transmission systems, they do not require massive inductive and capacitive components, like SVCs do. STATCOM requires less area due to its smaller size and has a higher reactive output at low system voltages [10].

C. Thyristor Controlled Series Compensators (TCSC)

TCSC is an extension of conventional series capacitors but only addition of thyristor-controlled reactor with it. A continuous and rapid changing series compensation system may be achieved by connecting a reactance in parallel with a series capacitor. Increased actual transfer power, power oscillations damping, sub-synchronous resonances damping, and power flow line control are the major benefits of TCSCs [11]–[13].

D. Unified Power Flow Controller (UPFC)

A unified power flow controller (UPFC) is the most promising device in the FACTS concept. It can modify the three control parameters, namely the bus voltage, transmission line reactance, and phase angle between two buses, concurrently or separately. The in-phase voltage, quadrature voltage, and shunt compensation are all controlled by a UPFC. UPFC is combination of shunt connected device (STATCOM) and a series branch (SSSC) in the transmission line via its DC link. This device is the most multipurpose FACTS device. It can not only perform the function of STATCOM, TCSC and phase prevent faults, it can also mitigate the effects of faults and make electricity supply more secure by reducing the number of line trips [14].

E. Other FACTS Controllers

Thyristor Controlled Phase Angle Regulator (TCPAR) is manly used for phase angle control, transient stability, and damping of oscillations. Short Circuit Current Limiter (SCCL) is simply a reactor that is combined with a TPSC (Thyristor Protected Series Compensator). It limits the short circuit level by operating at zero impedance during steady state condition and increases the impedance during short circuit scenarios. The NGH is mainly deployed to counter SSR (Sub-Synchronous Resonance). It is used for dampening oscillations, transient stability, and series impedance control. The thyristor switched series capacitor (TSSC) is a fixed series capacitor with a thyristor based static switch connected across the capacitor. The capacitor is bypassed when the thyristors are conducting and inserted into the circuit when they are not conducting. The TSSC provides variable capacitive compensation. Thyristor Control Breaking Resistor (TCBR) consist of a resistor in series with a bidirectional thyristor valve. It is mainly inserted to improve the stability of the network during the presence of disturbances.

III. TECHNICAL APPLICATIONS AND BENEFITS OF FACTS DEVICES

The technical application and main benefits of FACTS controllers include but not limited to solving the following problems: Addressing steady state problems (Problems of voltage limit, Problems of thermal limits, Problems of short circuit levels, and Problems of sub-synchronous resonance), addressing dynamic stability problems (problems of transient stability, damping, post contingency voltage control, and voltage stability). Tables I and II provide a detailed survey of which FACTS controllers can be used to address steady state and dynamic state problems respectively as well as conventional solutions [15]–[17].

TABLE I. Survey of Steady State Problems with their Conventional and FACTS Controller Solutions

Steady State Applications of FACTS				
Problems		**Corrective Action**	**Conventional Solution**	**FACTS Controller**
Voltage Limits	Low voltage at heavy load	Supply reactive power	Shunt capacitor, series capacitor	SVC STATCOM
	High voltage at light load	Remove reactive power supply	Switch EHV and/or shunt capacitor	SVC TCSC STATCOM
	High voltage following outage	Absorb reactive power	Switch shunt capacitor, series capacitor	SVC STATCOM
Thermal limits	Line or transformer over	Reduce load	Add line or transformer	TCSC UPFC TCPAR
	Tripping of parallel circuits	Limit line loading	Add series reactor, capacitor	UPFC TCSC
Loop flow	Parallel line load sharing	Adjust series reactance/phase reactance. Rearrange network or use thermal limit actions	Add series capacitor and PAR	UPFC TCSC TCPAR
	Post fault sharing	PAR, series capacitor/reactor	PAR, series capacitor / reactor	TCSC UPFC SVC TCPAR
	Flow direction reversal	Adjust phase angle	PAR	TCPAR UPFC
Short circuits Levels	Excessive breaker fault current	Limit short circuit Limit short circuit current	Add series reactor, new circuit breaker	SCCL UPFC TCSC
Sub-synchronous resonance	Potential turbine/generator shaft damage	Mitigate oscillations	Series compensation	NGH TCSC

IV. PERFORMANCE COMPARISON

The relative efficacy of different FACTS controllers in enhancing power system performance is investigated in [18]. SVC, STATCOM, UPFC, and IPFC control channels have all been subjected to similar research in [19]. Nelson et al [20] compared and assessed four FACTS controllers: the SVC, the STATCOM, the TCSC, and the UPFC. The STATCOM outperforms the SVC among the shunt controllers. The TCSC is more effective than the other series controllers because it allows for more precise regulation of power flow in the line. The UPFC is by far the finest controller since it allows for independent control of the bus voltage as well as the real and reactive power flows on the line. Table III compares different FACTS controllers in terms of performance in load flow control, voltage control, transient stability, and dynamic stability [15], [21]–[23].

TABLE II. Survey of Dynamic State Problems with their Conventional and FACTS Controller Solutions

Dynamic Application of FACTS				
Problems		**Corrective Action**	**Conventional Solution**	**FACTS Controller**
Transient stability	Remote generation, Interconnected areas, loosely meshed network	Increase synchronizing torque	High response exciter, series capacitor	TCSC TSSC UPFC
	Remote generation, loosely meshed network	Absorb kinetic energy	Breaking resistor, Fast Valuing Turbine	TCBR
	Interconnected areas, Tightly meshed network loosely meshed network	Dynamic load flow control	HVDC	TCPAR UPFC TCSC
Dampening	Remote generation	Dampen frequency oscillations	Exciter, Power System Stabilizer	SVC TCSC STATCOM
	Interconnected areas, loosely meshed network	Dampen low frequency oscillations	Power System Stabilizer	SVC TCPAR UPFC NGH TCSC STATCOM
Post contingency voltage control	Remote generation, Interconnected areas, loosely meshed network	Dynamic voltage support	Automatic Voltage Regulator	SVC, STATCOM UPFC
		Dynamic flow control	Automatic Voltage Regulator	SVC UPFC TCPAR
		Dynamic voltage support and flow control	Automatic Voltage Regulator	SVC UPFC TCSC
	Remote generation, Interconnected areas, Tightly Meshed network, loosely meshed network	Reduce impact of contingency	Parallel lines	SVC TCSC STATCOM UPFC
Voltage stability	Interconnected areas, Tightly meshed network, loosely meshed network	Reactive support	Shunt capacitor, Shunt reactor	SVC STATCOM UPFC
		Network control action	LTC, Enclosing HVDC controls	TCSC STATCOM UPFC
		Generation control	High response exciter	SVC STATCOM UPFC
		Load control	Under voltage load shedding	TCSC SVC STATCOM UPFC

TABLE III. Performance Comparison of Various FACTS Controllers

No	FACTS Controller	Load Flow Control	Voltage Control	Transient Stability	Dynamic Stability
1	UPFC	High	High	Medium	Medium
2	STATCOM	Low	High	Medium	Medium
3	SVC	Low	High	Low	Medium
4	TCSC	Medium	Low	Low	Medium
5	SSSC	Low	High	Medium	Medium

V. ECONOMIC EVALUATION AND COMPARISON OF FACTS CONTROLLERS

The value of FACTS applications lies mainly in the ability of the transmission system to reliably transmit more power or to transmit power under more severe contingency conditions with the control equipment in operation. If the value of the added power transfer over time is compared to the purchase and operational costs of the control equipment, relatively complex and expensive applications may be justified [24]. The market structure, transmission tariff, and identification of winners and losers are among the other economic factors mentioned in [25]. Table IV presents the market value of selected FACTS controllers and other few traditional compensators [21], [26], [27].

TABLE IV. Market Value of Different FACTS Controllers and Traditional Compensators

No	FACTS Controller	Cost $/kVar
1	SVC	28.98
2	TCSC	28.98
3	STATCOM	36.22
4	UPFC Series Portions	38.91
5	UPFC Shunt Portions	38.91
Traditional Compensators		
1	Shunt Capacitor	5.80
2	Series Capacitor	14.49

A. *Investment Analysis of FACTS Controllers*

The capital cost or initial investment cost, operating and maintenance expenditures, the decrease in generation cost as a result of the installation of FACTS controllers, and the investment's economic life must all be included in a complete study of the investment in FACTS device [28], [29]. As a result, before making a purchase, the final choice must be thoroughly planed. There are a variety of financial analysis tools that can be used to aid in the evaluation of an investment choice. Some of the techniques utilized in the financial analysis process include the Net Present Value (NPV), Payback Period (PBP), Internal Rate of Return (IRR, and Life Cycle Cost (LCC) [28], [30].

Payback Period (PBP): A simple but extensively used approach of dividing an investment by project savings over time. This allows for the calculation of the time it will take to recoup the initial investment. The mathematical expression for PBP is shown in equation (1) [29].

$$n_{year} = \frac{\mathrm{Cost}_{FACTS}}{S_{v_{yearly}} - M_T} \qquad (1)$$

where n_{year} is the payback period Cost_{FACTS} is the initial investment cost of the FACTS controller, $S_{v_{yearly}}$ is the annual saving, M_T is the maintenance cost.

Net Present Value (NPV): This approach transforms future expenses and revenues to today's values so that the internal cash cost, or necessary rate of return, may be compared. A positive number denotes that the project will yield a profit, otherwise, it is not recommended to invest. NPV has historically been the most commonly utilized approach [30], and it is hence suggested for future economic projections of FACTS controllers. Mathematically, NPV is expressed in (2) [30].

$$NPV = \sum_{T=1}^{T} \frac{S_v - M_T}{(1+r)^T} - C_{inv} \qquad (2)$$

where T is the lifetime of the FACTS controller, S_v is savings incurred over the year due to the installation of the FACTS controller, r is the discount rate, and C_{inv} is the initial cost of investment of the FACTS controller.

Internal Rate of Return (IRR): IRR is determined from NPV; however, this method requires changing the discount rate until NPV equals zero. A project with an IRR higher than the needed (specified) rate of return is worthwhile to pursue.

LCC (Life Cycle Costs): It utilizes the NPV and instead of assessing a needed rate of return, LCC simply looks at the expenses connected with the project's life cycle. The LCC with the lowest value is favoured.

VI. CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

In this paper, a survey and comparison of different FACTS controllers with respect to system enhancement and economic consideration has been carried out in detail. It is found that the overall performance of the UPFC is by far higher for power system performance enhancement as compared to other FACTS controllers such as SVC, TCSC, STATCOM, and SSSC, however, its cost is the highest.

The data that has been presented in this paper is based on past and recent research papers about FACTS controllers and their applications. The conclusions are obtained from the studied papers and the actual situation of the market. The paper surveys FACTS controller's role in various aspects of power system, the practical consideration in the application and their economic value. FACTS devices versatility and technical benefits offer great opportunities in modern power system, and there are already plenty of work focusing on every one of the technical benefits FACTS controllers can bring.

From a planning point of view, the performance of the same FACTS controller under multi-operating condition should be tested to decide the optimal location and settings to justify the technical benefits of FACTS controllers. Very few works have been published focusing on this. It was found that very limited literature on valuing the economic benefits of FACTS devices. The main problem is that FACTS devices affect everything, from operation, transmission utilization, security and reliability scenario to the electricity market and its components it is therefore recommended for future research in this area.

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REFERENCES

[1] A. A. Edris, ‘Proposed Terms and Definitions for Flexible AC Transmission System (FACTS)’, *IEEE Trans. Power Deliv.*, vol. 12, no. 4, 1997.

[2] N. G. Hingorani and L. Gyugyi, *Understanding FACTS : concepts and technology of flexible AC transmission systems*. IEEE Press, 2000.

[3] F. M. Echavarren and L. Sigrist, ‘Stability Considerations for Transmission System Planning’, in *Transmission Expansion Planning: The Network Challenges of the Energy Transition*, Springer, Cham, 2021, pp. 201–248.

[4] W. Long and S. L. Nilsson, ‘Introduction to Flexible AC Transmission Systems (FACTS) Controllers: A Chronology’, pp. 3–12, 2020.

[5] M. A. Bhaskar, C. Subramani, M. J. Kumar, and S. S. Dash, ‘Voltage profile improvement using FACTS devices: A comparison between SVC, TCSC and TCPST’, *ARTCom 2009 - Int. Conf. Adv. Recent Technol. Commun. Comput.*, pp. 890–892, 2009.

[6] S. O. Faried, R. Billinton, and S. Aboreshaid, ‘Probabilistic technique for sizing FACTS devices for steady-state voltage profile enhancement’, *IET Gener. Transm. Distrib.*, vol. 3, no. 4, pp. 385–392, 2009.

[7] J. N. Rai, N. Hasan, R. K. Gupta, R. Kapoor, and R. Garai, ‘Enhancement of voltage profile of transmission line by using static var compensator’, in *National Electrical Engineering Conference (NEEC-2011) on Power and Energy Systems for Tomorrow*, 2011, vol. 2, no. 5, pp. 1921–1925.

[8] R. Nagananthini, ‘Series and shunt compensation in UPFC using cascaded multilevel inverter - A transformless approach’, *Int. Res. J. Eng. Technol.*, p. 1289, 2008.

[9] M. Haikal Aziz, M. H. Mansor, I. Musirin, S. Jelani, and S. A. Ismail, ‘Optimal placement of static VAR compensator in transmission network for loss minimization and voltage deviation index reduction’, *Int. J. Adv. Technol. Eng. Explor.*, vol. 8, no. 75, pp. 405–411, 2021.

[10] R. S. Camargo, A. E. A. Amorim, E. J. Bueno, and L. F. Encarnação, ‘Novel multilevel STATCOM for power system stability enhancement on DFIG-based wind farms’, *Electr. Power Syst. Res.*, vol. 197, p. 107316, Aug. 2021.

[11] M. Rashid Zaidan, S. I. Toos, and S. T. Hussain, ‘Impact of using TCSC on Power System Stability’, *World J. Eng. Res. Technol. www.wjert.org ISO*, vol. 5, no. 6, pp. 238–251, 2015.

[12] S. L. Nilsson and M. M. de Oliveira, ‘Technical Description of Thyristor Controlled Series Capacitors (TCSC)’, pp. 253–297, 2020.

[13] S. V. Smolovik, V. S. Chudny, A. S. Liamov, I. E. Ryndina, and A. I. Denisenko, ‘Application of a Static Synchronous Series Compensator to Increase the Transient Stability of a Powerful HPP’, in *Proceedings of the 2021 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering, ElConRus 2021*, pp. 1562–1565.

[14] B. Abdelkrim and Y. Merzoug, ‘Robust stability power in the transmission line with the use of a UPFC system and neural controllers based adaptive control’, *Int. J. Power Electron. Drive Syst.*, vol. 10, no. 3, pp. 1281–1296, 2019.

[15] R. K. Bindal, ‘A Review of Benefits of FACTS Devices in Power System’, *IJEAT*, vol. 3, no. 4, pp. 105–108, 2014.

[16] E. Barrios-Martínez, C. Ángeles-Camacho, E. Barrios-Martínez, and C. Ángeles-Camacho, ‘Technical comparison of FACTS controllers in parallel connection’, *J. Appl. Res. Technol.*, vol. 15, no. 1, pp. 36–44, Feb. 2017.

[17] S. Naveen, A. Piyush, N. Singh, and P. Agnihotri, ‘Power system stability improvement using FACTS devices’, 2018.

[18] J. Chang and J. H. Chow, ‘Time-optimal series capacitor control for damping interarea modes in interconnected power systems’, *IEEE Trans. Power Syst.*, vol. 12, no. 1, pp. 215–221, 1997.

[19] M. A. Abido and K. P. O. Box, ‘Power System Stability Enhancement using FACTS Controllers: A Review’, *Arab. J. Sci. Eng.*, vol. 34, p. 1, 2009.

[20] R. J. Nelson, ‘Transient stability enhancement with FACTS control’, *Sixth Int. Conf. AC DC Power Transm.*, vol. 1996, pp. 269–274, 1996.

[21] V. G. Mathad, B. F. Ronad, and S. H. Jangamshetti, ‘Review on Comparison of FACTS Controllers for Power System Stability Enhancement’, *Int. J. Sci. Res. Publ.*, vol. 3, no. 1, pp. 2250–3153, 2013.

[22] A. Sode-Yome, N. Mithulananthan, and K. Y. Lee, ‘A comprehensive comparison of FACTS devices for enhancing static voltage stability’, *2007 IEEE Power Eng. Soc. Gen. Meet. PES*, 2007.

[23] A. K. Mohanty and A. K. Barik, ‘Power System Stability Improvement Using FACTS Devices’, *InternJournal Mod. Eng. Res.*, vol. 1, no. 2, pp. 666–672, 2011.

[24] D. G. Ramey and M. Henderson, ‘Overview of a special publication on transmission system application requirements for FACTS controllers’, *2007 IEEE Power Eng. Soc. Gen. Meet. PES*, 2007.

[25] F. B. Alhasawi, J. V. Milanović, and A. A. Alabduljabbar, ‘Economic viability of application of FACTS devices for reducing generating costs’, *IEEE PES Gen. Meet. PES 2010*, 2010.

[26] M. Saravanan, S. M. R. Slochanal, P. Venkatesh, and J. P. S. Abraham, ‘Application of particle swarm optimization technique for optimal location of FACTS devices considering cost of installation and system loadability’, *Electr. Power Syst. Res.*, vol. 77, no. 3–4, pp. 276–283, Mar. 2007.

[27] M. Duarte, ‘Economic Appraisal and Cost-Benefit Analysis’, pp. 709–751, 2020.

[28] A. Baggini and F. Bua, ‘Costs: Investment analysis for PQ solutions’, *Power Qual. Appl. Guid.*, pp. 1–12, 2004.

[29] A. A. Alabduljabbar and J. V. Milanović, ‘Assessment of techno-economic contribution of FACTS devices to power system operation’, *Electr. Power Syst. Res.*, vol. 80, no. 10, pp. 1247–1255, 2010.

[30] F. B. Alhasawi and J. V. Milanović, ‘Techno-economic contribution of FACTS devices to the operation of power systems with high level of wind power integration’, *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1414–1421, 2012.