A Review on Control Strategies for Integration of Electric Vehicles with Power Systems

Prashant Akhade, Masood Moghaddami, Amir Moghadasi and Arif Sarwat
Electrical and Computer Engineering, Florida International University, Miami, Florida 33174, Email: asarwat@fiu.edu

***Abstract*—Electric vehicles (EVs) are considered as portable sources of power which can be integrated with any infrastructure, including power grid at different geographical locations, forming a dynamically varying system. Grid-to-vehicle (G2V) and vehicle-to-grid (V2G) connections are considered as essential parts of the future smart grids which can considerably enhance the performance of the system in different aspects. The control strategy for integration of EVs plays a key role in enhancing the performance of power system. The aim of this paper is to study different types of control strategies for integration of electric vehicles with power grid. The control strategies that are used for G2V and V2G connections include multi-agent control, frequency control, aggregated control, virtual synchronous machine-based control, etc. which are reviewed in detail. Detailed comparisons between these control methods are presented in this paper. This paper further highlights the transient stability of power system on both distribution and wide-area levels.**

***Index Terms*—control, electric vehicle, grid to vehicle, power system, vehicle to grid.**

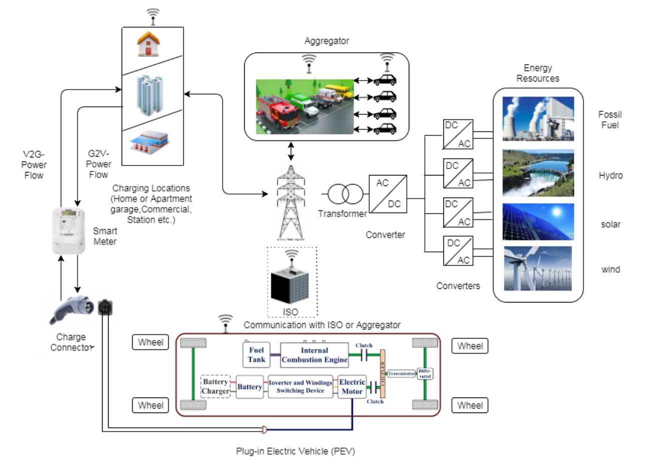

Fig. 1. Structure of a smart grid integrated with electric vehicles (EVs).

I. Introduction

Electric vehicles (EVs) are considered as clean alternatives for conventional internal combustion engines (ICEs) which can significantly contribute to the carbon foot print reduction. About one-fifth of the global energy is used for transportation systems. Moreover, EVs are more than 60% efficient compared to 17%-21% efficiency of ICEs [1]. Thus, EV technology has recently gained an increasing interest in transportation systems. EVs are considered as portable sources of power which can be integrated with power grid at different locations. A grid-integrated EV (GIEV) is described as a vehicle which is partially or fully powered by electric motor, and thereby powered by an onboard traction battery that can be charged via using a grid-connected battery charger. GIEV includes both G2V as well as V2G connections. Depending on their power flow characteristics EV chargers may be unidirectional, only allowing Grid to Vehicle (G2V) operation; or duplex, allowing G2V and Vehicle to Grid (V2G) operation [2], [3]. PHEVs has few advantages over HEVs and ICVs as they can perform discharging operation in case of V2G devices and charging operation in case of G2V devices. They can play essential roles in case of Smart metering, communication, and control systems which directly coordinates between V2G and G2V modes of operation as shown in Fig. 1 [4], [5]. Such G2V and V2G connections can be also established using inductive charging systems [6]–[9].

One of the underlying challenges of regulating the grid is assuring a steady balance of both supply and demand. In absence of such balance, a damage would be damaged briskly to our electrical equipment and deterioration in our corresponding energy supply. As most of the part of grid leads to shortages in their considerable storage in order to smooth fluctuations in both demand and supply, grid operators are flexible to balance generation and consumption nearly matched. Regarding grid connection aspects electric vehicles have some challenges such as PHEVs charging problem, the influence of charging loads on the grid, optimizing charging schedule of PHEVs [10]. Even though EVs can then be regarded as flexible performers in the smart grid, V2G comes with additional costs for battery degradation and power electronics. V2Gs are the possible solutions for enhancing future smart grid resiliency by supporting power grid. In extreme weather conditions where there are cases of power outages, they can be used as power sources to provide power for critical loads, and in some infrastructures, such as hospitals, cell tower and other emergency situations where there is an increase in need of such power sources.

In this paper, various control strategies that are used for integration of EVs with power grid are reviewed. Also their advantages and disadvantages are discussed depending on their respective transient stability of the power system based on their transmission and distribution levels. Likewise, review of each type of the control strategy will be presented and also study of various such control strategies will be described in detail and simultaneously discussion and explanation based on their characteristics, performance, efficiency, reliability, benefits, drawbacks and other such aspects will be examined.

II. Multi-Agent Control Strategies

Multi-agent control (MAC) strategy is used for handling charging operation of EV in LV distribution networks as explained in [11], [12]. It comprises of two or many smart agents and each with a local goal that permits attaining a global objective in absence of principal control. The primary advantage of MAC includes autonomy, reduced maintenance, extensibility, and fault tolerant [13]. The advantages of MAC strategies include flexibility which is used to carry out under variously distributed generator (DG) and EV penetration levels. The other one is scalability which includes service restoration for various size testing systems, both minimum and maximum; and sturdiness which demonstrates a potential to carry out proficiently for a single as well as multiple-liable situations [14]. MAC makes its usage in problems of controlling power systems which comprises outage management and service restoration, microgrid control, and virtual power plant control. The decentralized MAC-based methods which use three layer architectures is represented in Fig. 2 [15], [16].

It was verified that MAC techniques outstrip the centralized one according to computational time and scalability. This MAC makes use of a three-layer architecture which is same as [12], [17]. MAC can also be used as a Self-Healing system where the system is capable of auto-detection and functionality recovery when it is faced casualty where the events can be single or many in number terming as self-healing. In power system context, the definition includes steps such as identifying the problems quickly, to promote any actions in order to reduce any severe effects due to casualties, and recovery of prompt conditions of this process to an operating state stabilization [18], [19]. Reactive stage in case of emergency and stage of restoration are mainly two type of different stages relating to self-healing process. MAC are specifically suited for building systems to evaluate complex problems which is not possible to be solved by any one agent by itself, interacting to such problems which comprises of multiple problem-solving methods needs various such types of expertise and also knowledge or where there are such more viewpoints, developing systems where dynamic reorganization is necessary, jobs in which the information resources are disseminated so these are where MAC finds applications in. Most main advantages of MAC technology consists of Extensibility, flexibility, reliability, robustness, computationally efficient and with optimal speed, developed and maintainable, reusable, less cost. As far as the challenges of MAC are concerned, it still has challenges like there are numerous problems while designing and their implementation like their proficient and operative interacting protocols, devising their task and its problems, disintegration, providing task to each agents and synthesis of their subtask, identification of agent, exploration and open system location , constant and coherent model behavior when preventing detrimental connections, representing data regarding environment state, and also action and awareness of other agents, creation of team and organization and algorithms which are quite effective in terms of planning and learning .

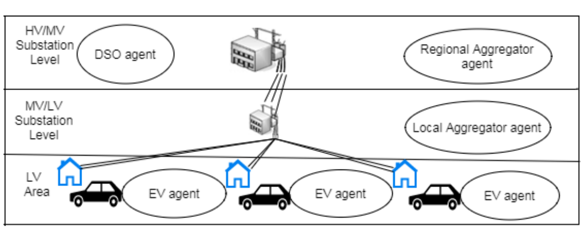

Fig. 2. Hierarchy in multi-agent control method.

MAC can be classified as closed MAC and open MAC. closed MAC consists of designs which are static along with pre-assigned modules and their functionality. The characteristics of such system is previously known such as shared dialect, every agent can be industrialized as an skillful, supportive agents , development of the system can be contributed by more than one developers that too at the same time. For instance, when referring MAC to an organization. Advantages consists of load distribution, expertness, comprehensible and likelihood, as elements here are already acknowledged, And also there is an identification of interactive protocols and language, It has supportive agents and they share their architecture and software. It includes disadvantages as follows, cost in terms of maintenance can be very huge, which may include minimal tolerance in faulty situations, Tedious to collaborate with another systems. Another type of MAC is open MAC and in this the system doesn't includes any of prior static design, and has only one agent within. Agents here are not certainly conscious about others such as process for detecting, examining and tracing others is necessary.

III. Aggregated Control Strategies

It introduces a storage strategy of aggregator and several electric vehicles. According to [20], sustainable operation via driving statistics simulation of the electric vehicles is verified. The scheduled charging is autonomously satisfied in this type of control strategy, the centralized V2G and G2V accomplishes the global power and energy management dispatched to the several electric vehicles. Logical or control connection is essential for communicating with an aggregator. The aggregator is however accountable for the request to the secondary control market for providing symmetrical control power and allowing communication with the TSO on the one part and with the electric vehicles with that of another part and by assuming both generations of renewable energy and aggregated electrical loads in case of distribution feeders, further analysis is being employed based on it.

The aggregated storage policy for aggregator and several electric vehicles and the in order to alleviate influences on the charging process of the vehicle to that of distribution scheme and allows an integration of not only EVs but also the renewable energy resources into that of the power system. In such type of scheme, each vehicle both charging request and battery management, which is considered to be imperative for vehicle application and usage, is achieved with the help of the independent scheduled charging system. Furthermore,

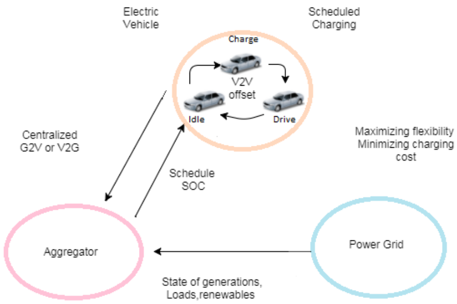

Fig. 3. Aggregated integration of EVs with power grid.

control signals will be reported by an aggregator for the case of universal power and managing energy unit relating to EVs which is idle. Not only limited to these aspects but additional details regarding compromising examination in terms of the losses in the amount of energy and its demanding configurations such as the renewable energy resources which is considered to be one of the valuable data for the figures of the operation of that of electric vehicle aggregator.

For example, only an amount of 38.2% of the net capacity of the battery from the fleet of an aggregated PHEV relating to numerous cars can be obtainable for the provision of fixed control of positive or negative reserve power at each and every time in that specified time period [21]. The manager directly makes use of the common LFC with the help of power reserves from aggregated type along with matchlessly transmitting them from their given set of existing capacity as per the grids requirements. Aggregated control reserve power can be matchlessly transmitted, from the chosen, a set of usable control reserve capacity as per the grids requirements, along with the reduction in the utilization charges for that of actuators and respective technical restrictions such as increasing and time varying obtainability of actuators. In the situation where it is consisting of combined battery capacity from that of fleets of PHEV as added control reserve capacity at removal, this energetically rapid responding battery capacity can also be used for governing comparatively slight and changing frequency conflicts and in such cases only PHEVs are taken into account for the provision of such additional control reserve power.

IV. Load-Frequency Control of EV Connections

The description of load frequency concepts is introduced and approaching towards common features of frequency control services, balancing the given frequency at its goal value needs the active power to be created and used up which is balanced to maintain the load and the generation side to be stable. A specific amount of active power which is also related to frequency control reserve is kept accessible to make this control. It introduces with three such control structures are introduced for frequency reserves which are classified as primary, secondary and tertiary. Generally, the TSO offers these three types of such control in stated quantities for each their corresponding control area, both in terms of positive, where there is an increase in the generation side and there is a corresponding decrease in load and negative, where there is a decrease in generation side and the corresponding increase in load increase. The quantity relies on the dimension and generation set of the control area [23].

The load frequency control (LFC) by V2G can be attained by adequately control of charging and discharging schemes of the electric vehicles as per LFC signal. Central load dispatching center dispatches the LFC signal and considered to be transmitted to the EVs through the locally controlled centers.

The frequency analysis pattern as demonstrated in Fig. 3 finds usage in this paper. The simulation in the period can be done by such model of from numerous 1 hour to 24 hours. The design comprises of a thermal power model, generator design, wind power design, photovoltaic generation design, EDC (Economic dispatch control) scheme design, load design, EV design and LFC scheme design as shown in Fig. 4. LFC model generates the LFC signal.

V. Virtual Synchronous Machine-Based Control

In virtual synchronous machine (VSM) type of control strategy, The inertia and it's related damping outcome of synchronous machine are being matched by controlling the power converter. Hence, the corresponding regulation of frequency and spinning reserve can be efficiently dealt by VSM-based charger in case of EV in power systems. The situations where there are outages in the grid, the VSM is able to undoubtedly institute an islanded operation of grid and can provide the battery's local load connected to the EV. In a single phase circuit, To prevent the impact of power oscillations on the virtual inertia, This type of control strategy merely depends on a virtual two-phase system for computing powers in case of active and reactive.

An assuring control strategy, which is used to provide distributed ancillary services and its purpose is to address the recent concept of VSM as explained in [26]–[31]. Such control strategy can essentially assure inertia imitation, frequency control and also voltage control, local reactive power. Albeit the VSM type of control strategy were initially planned for applications like in renewable as well as distributed type of

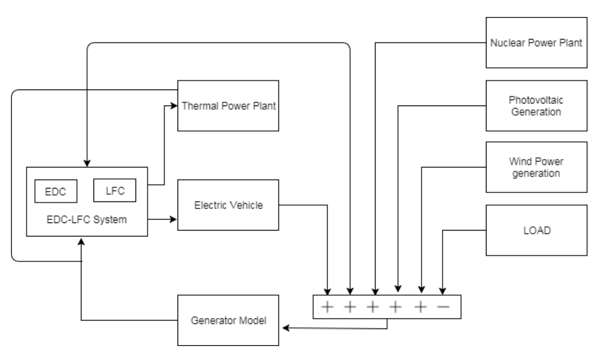

Fig. 4. Load-frequency control strategy for integration of EVs with power grid.

TABLE I
COMPARISON BETWEEN DIFFERENT CONTROL STRATEGIES FOR INTEGRATION OF EVS WITH POWER GRID

Control Strategy	General advantages	General disadvantages
Multi-agent control [11]–[19]	• uses fleet of EVs to achieve various global objectives according to the requirements • can satisfy grid-requirements in real-time • controls a wide area and therefore can increase grid resiliency in larger scale	• requires two-way communication between agents and utility • requires extensive authorization from EV users • experiences instability in its system but can be stabilized using energy capacitor system
Aggregated control [20]–[22]	• can control fleet of EVs • increases power system • exhibits linearity in its system	• low speed response • The grouping process needs to be completed before using this type of control strategy • introduces overhead in its system but can be controlled using Model predictive control technique
Load-frequency control [23]–[25]	• significantly enhances the stability of the system • balances the actual frequency with the desirable power output (megawatt) in the interconnected power system and changes controllable in tie line power between control areas are achieved • maintains demand along with supply and frequency regulation in power systems • autonomous, reduced maintenance, extensible, fault tolerant, and flexible	• It exhibits load disturbances in the system • experiences instability in the system but the stability system can be addressed with a type of tuned PID controller which can thereby handle the load disturbances and retrieve the system stability quickly • experiences non-linearity in its model
Virtual synchronous machine control [26], [27]	• enhances the stability of the system by providing virtual inertia • provides a flexible control with wide range of variables • communication is not required	• implementation of controller is complex • experiences instability in the system but can can eliminated by studying its parameter sensitivity of pole location • sensitivity to the parameters settings • exhibits non-linearity in its state space model

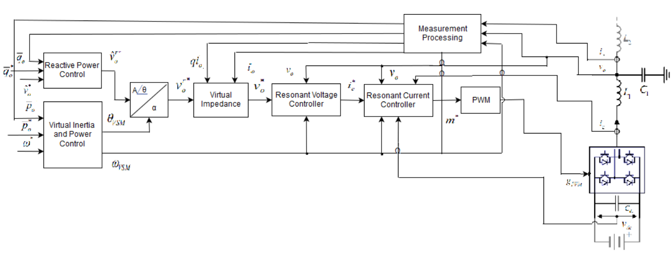

Fig. 5. A typical virtual synchronous machine (VSM) based control method.

generation systems, facility of auxiliary related services from the EV chargers which are VSM controlled has been explained in [32]–[34], earlier proposed techniques for in case of VSM-related control have concentrated on power converters which are of three-phase.

In a case of the control system of VSM in case of a single-phase, an outline for the utilized control strategy in case of a single phase VSMs as demonstrated in Fig. 5 . In the case of examined event, the power circuit comprises a H-bridge type of converter which is single phased is connected to grid via LCL or LC type of filter, as showed in the diagram. The converters dc side capacitor is considered to be one of the controlled load or source. To determine the dc bus voltage Vdc, the converters output current ic, the the filter capacitor voltage vo and the corresponding output current io from the LC filter, sensors are used. In figure. 5. The symbols shown in upper case in the circuit specifies physical quantities, whereas symbols shown in lower case displays per unit quantities which is used in the control system.

The VSM type of control strategy are efficient for offering ancillary services such as their contribution in main LFC, inertia imitation for spinning reserve, reactive power regulation or local voltage. In case islanded process, the presented design of this kind of strategy also has the intrinsic ability to feed local loads. Hence, the VSM-type of control strategy can be one of the preferred choices for offering Vehicle-to-Grid (V2G) services in local battery chargers in case of single-phase for EVs [35]. The comparisons between different control strategies for integration EVs with power grid are summarized in TABLE I.

VI. CONCLUSION

In this paper, various control strategies based on V2G and G2V connections are being investigated. VSM type of control strategy experiences instability in its system but can be stabilized by studying the parameter sensitivity of their corresponding pole locations, it exhibits nonlinearity in the case of their state space model and is usually complex (especially in the case of an islanding operation). Multi-agent system also experiences instability in its system but can be stabilized using a proposed energy capacitor system. Regarding Load frequency control the instability in their functionalities can be eliminated by making the use of a specific tuned PID controller to handle the load disturbances and retrieve the system stability quickly. Aggregated control does not exhibit constant speed but can be controlled using Model predictive control technique. VSM method can improve grid stability in terms of power system stability but it requires a complex controller design. Aggregated and Multi-agent type of control strategies prove to be a preferred choice for wide area control.

REFERENCES

[1] C. H. Tie, C. K. Gan, and K. A. Ibrahim, "The impact of electric vehicle charging on a residential low voltage distribution network in malaysia," in *2014 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*, May 2014, pp. 272–277.

[2] J. A. P. Lopes, F. J. Soares, and P. M. R. Almeida, "Integration of electric vehicles in the electric power system," *Proceedings of the IEEE*, vol. 99, no. 1, pp. 168–183, Jan 2011.

[3] J. Liu, "Electric vehicle charging infrastructure assignment and power grid impacts assessment in beijing," *Energy Policy*, vol. 51, no. C, pp. 544–557, 2012. [Online]. Available: http://EconPapers.repec.org/RePEc:eee:enepol:v:51:y:2012:i:c:p:544-557

[4] J. Hossain and A. Mahmud, *Renewable energy integration: challenges and solutions*. Springer Science & Business Media, 2014.

[5] S. Mocci, N. Natale, F. Pilo, and S. Ruggeri, "Demand side integration in lv smart grids with multi-agent control system," *Electric Power Systems Research*, vol. 125, pp. 23–33, 2015.

[6] M. Moghaddami and A. Sarwat, "Self-tuning variable frequency controller for inductive electric vehicle charging with multiple power levels," *IEEE Trans. Transport. Electrific.*, vol. 3, no. 2, pp. 488–495, June 2017.

[7] M. Moghaddami, A. Anzalchi, and A. I. Sarwat, "Single-stage three-phase ac-ac matrix converter for inductive power transfer systems," *IEEE Trans. Ind. Electron.*, vol. 63, no. 10, pp. 6613–6622, Oct 2016.

[8] M. Moghaddami, A. Anzalchi, A. Moghadasi, and A. Sarwat, "Pareto optimization of circular power pads for contactless electric vehicle battery charger," in *2016 IEEE Industry Applications Society Annual Meeting*, Oct 2016, pp. 1–6.

[9] M. Moghaddami, A. Anzalchi, and A. I. Sarwat, "Finite element based design optimization of magnetic structures for roadway inductive power transfer systems," in *2016 IEEE Transportation Electrification Conference and Expo (ITEC)*, June 2016, pp. 1–6.

[10] C. Zhang, Q. Huang, J. Tian, L. Chen, Y. Cao, and R. Zhang, "Smart grid facing the new challenge: The management of electric vehicle charging loads," *Energy Procedia*, vol. 12, pp. 98–103, 2011.

[11] K. Shimizu, T. Masuta, Y. Ota, and A. Yokoyama, "Load frequency control in power system using vehicle-to-grid system considering the customer convenience of electric vehicles," in *Power System Technology (POWERCON), 2010 International Conference on*. IEEE, 2010, pp. 1–8.

[12] F. Bliek, A. van den Noort, B. Roossien, R. Kamphuis, J. de Wit, J. van der Velde, and M. Eijgelaar, "Powermatching city, a living lab smart grid demonstration," in *Innovative Smart Grid Technologies Conference Europe (ISGT Europe), 2010 IEEE PES*. IEEE, 2010, pp. 1–8.

[13] N. Masuch, J. Keiser, M. Lützenberger, and S. Albayrak, "Wind power-aware vehicle-to-grid algorithms for sustainable ev energy management systems," in *Electric Vehicle Conference (IEVC), 2012 IEEE International*. IEEE, 2012, pp. 1–7.

[14] T. Markel, M. Kuss, J. Foster, D. Manz, M. Mahony, M. Nielsen, A. Reid, and R. D. Wilk, "The case for open-source pev charge management data framework," in *Electric Vehicle Conference (IEVC), 2012 IEEE International*. IEEE, 2012, pp. 1–5.

[15] R. G. Gago, S. F. Pinto, and J. F. Silva, "G2v and v2g electric vehicle charger for smart grids," in *Smart Cities Conference (ISC2), 2016 IEEE International*. IEEE, 2016, pp. 1–6.

[16] A. Sharma, D. Srinivasan, and A. Trivedi, "A decentralized multiagent system approach for service restoration using dg islanding," *IEEE Transactions on Smart Grid*, vol. 6, no. 6, pp. 2784–2793, 2015.

[17] S. Vandael, N. Boucké, T. Holvoet, and G. Deconinck, "Decentralized demand side management of plug-in hybrid vehicles in a smart grid," in *Proceedings of the first international workshop on agent technologies for energy systems (ATES 2010)*, 2010, pp. 67–74.

[18] S. M. Amin and B. F. Wollenberg, "Toward a smart grid: power delivery for the 21st century," *IEEE power and energy magazine*, vol. 3, no. 5, pp. 34–41, 2005.

[19] K. Moslehi and R. Kumar, "Vision for a selfhealing power grid," *Abb Review*, vol. 4, pp. 21–25, 2006.

[20] E. Sortomme and M. A. El-Sharkawi, "Optimal combined bidding of vehicle-to-grid ancillary services," *IEEE Transactions on Smart Grid*, vol. 3, no. 1, pp. 70–79, 2012.

[21] A. Ulbig, M. D. Galus, S. Chatzivasileiadis, and G. Andersson, "General frequency control with aggregated control reserve capacity from time-varying sources: The case of phevs," in *Bulk Power System Dynamics and Control (iREP)-VIII (iREP), 2010 iREP Symposium*. IEEE, 2010, pp. 1–14.

[22] L. Zuccaro, A. Di Giorgio, F. Liberati, S. Canale, A. Lanna, V. F. Pallares, A. M. Blanco, R. U. Escobar, J. Ratej, B. Mehle *et al.*, "Smart vehicle to grid interface project: Electromobility management system architecture and field test results," in *Electric Vehicle Conference (IEVC), 2014 IEEE International*. IEEE, 2014, pp. 1–7.

[23] H. Liu, Y. Yang, J. Qi, J. Li, H. Wei, and P. Li, "Frequency droop control with scheduled charging of electric vehicles," *IET Generation, Transmission & Distribution*, vol. 11, no. 3, pp. 649–656, 2017.

[24] C. Zhao, U. Topcu, and S. H. Low, "Frequency-based load control in power systems," in *American Control Conference (ACC), 2012*. IEEE, 2012, pp. 4423–4430.

[25] D. Guha, P. K. Roy, and S. Banerjee, "Load frequency control of large scale power system using quasi-oppositional grey wolf optimization algorithm," *Engineering Science and Technology, an International Journal*, vol. 19, no. 4, pp. 1693–1713, 2016.

[26] H.-P. Beck and R. Hesse, "Virtual synchronous machine," in *Electrical Power Quality and Utilisation, 2007. EPQU 2007. 9th International Conference on*. IEEE, 2007, pp. 1–6.

[27] S. DArco, J. A. Suul, and O. B. Fosso, "A virtual synchronous machine implementation for distributed control of power converters in smartgrids," *Electric Power Systems Research*, vol. 122, pp. 180–197, 2015.

[28] Y. Chen, R. Hesse, D. Turschner, and H. Beck, "Dynamic properties of the virtual synchronous machine."

[29] K. Visscher and S. W. H. De Haan, "Virtual synchronous machines (vsgs) for frequency stabilisation in future grids with a significant share of decentralized generation," in *SmartGrids for Distribution, 2008. IET-CIRED. CIRED Seminar*. IET, 2008, pp. 1–4.

[30] Q.-C. Zhong and G. Weiss, "Synchronverters: Inverters that mimic synchronous generators," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 4, pp. 1259–1267, 2011.

[31] S. D'Arco and J. A. Suul, "Virtual synchronous machinesclassification of implementations and analysis of equivalence to droop controllers for microgrids," in *PowerTech (POWERTECH), 2013 IEEE Grenoble*. IEEE, 2013, pp. 1–7.

[32] C. Pelczar, *Mobile virtual synchronous machine for vehicle-to-grid applications*. Cuvillier, 2012.

[33] T. K. Vrana and C. Hille, "A novel control method for dispersed converters providing dynamic frequency response," *Electrical Engineering*, vol. 93, no. 4, pp. 217–226, 2011.

[34] J. A. Suul, S. D'Arco, and G. Guidi, "A single-phase virtual synchronous machine for providing vehicle-to-grid services from electric vehicle battery chargers," in *Proceedings of the International Electric Vehicle Technology Conference & Automotive Power Electronics*, 2014.

[35] ——, "Virtual synchronous machine-based control of a single-phase bi-directional battery charger for providing vehicle-to-grid services," *IEEE Transactions on Industry Applications*, vol. 52, no. 4, pp. 3234–3244, 2016.