

Article

A Review on Optimal Control for the Smart Grid Electrical Substation Enhancing Transition Stability

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Abstract: This paper is a research article for finding the optimal control of smart power substations for improving the network parameters and reliability. The included papers are the most essential and main studies in the field, which propose a different approach to reach the best performance in electrical power systems. The parameters for improvement are the ability for tracking of the reference signal, stabilizing the system, reducing the error in steady state and controlling the behavior in transient state. The research focuses with the reaching a better transient stability considering voltage and frequency dynamic parameters. The optimal model for the control is focused on minimizing energy consumption but maintaining the controllable parameters, exploring some optimization techniques to find the optimal control, with of aim of minimizing the response time, the energy consumption, and maximizing the reliability by means of improving the controller to be more robust.

Keywords: smart grid; control; substation; electrical; optimization; hierarchical; distributed generation; microgrid



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1. Introduction

The present paper aims to give an overview of different existing methodologies for optimal control in a smart power substation (SPSS). The main objective is to show several approaches for optimal control of a SPSS for improving the network transient stability, considering electrical variables as the frequency and voltage. The review explores the general models for integrating all the elements in a SPSS, taking into account that the control must be optimal, enhancing transition stability of the tackled variables.

The research has a worldwide impact because smart grid (SG) is one of the most promising technologies to fight against climate change; additionally, there are projects in the region, which aim to unify the generation, transmission, and distribution of energy to improve the stability of the entire system in the region. Finally, there is a massive gap in the regional energy network development, and the researchers' achievements to boost the technological advances in this field.

The document is organized as follows, Section 2 shows the applied methodology to understand a substation, Section 3 shows the State of the Art, Section 4 shows the definitions for SPSS and presents the control level in SPSS, and the strategies for optimal operation. Finally, the conclusions and future work are presented in Section 5.

2. Methodology

The methodology is based on the scientific information extracted from the state of the art (SoTA), where the most cited and relevant research were selected considering the documents which tackled the problem with a mathematical modeling and engineering simulation approach.

The methodology to control a SPSS is explained below in chronological order, see Figure 1. First, the establishment of the substation model is done, which will reach the plant model through soft computing identification techniques. In control engineering is essential to define that plant that is going to be controlled, and it is normal to implement several soft computing techniques, for instance, neural network or fuzzy logic and meta-heuristic applied to identify the system. In the identification process, complex variables of the power system can be included, implementing it as a dynamic system.

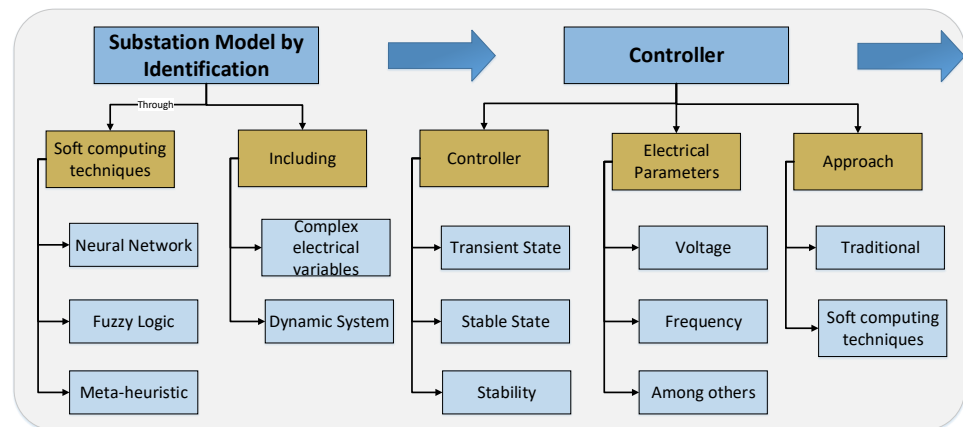


Figure 1. Comparison between a system with centralized and distributed generation.

Secondly, SPSS controller must be designed under criteria of improving the transient and stable behavior for the electrical parameters, for instance, voltage or frequency. SPSS is part of the distribution system DS when transforming into an automated energy system, specifically when located in the first level of SG.

The control techniques have to be implemented in the controller, using a traditional approach or soft computer techniques to reach a best performance in the general systems, for instance, improving tracking of the reference signal, stabilizing the system, reducing the error in the state, and controlling the behavior in transient state. Figure 2 shows a SG with all its constituent elements, among them, a microgrid MG with different resources is implemented, for instance photovoltaic (PV) generation, hydraulic power generation (HG), wind generation, combined heat and power (CHP) and electric vehicles (EV). Each of these types of generation have different characteristics and control techniques.

Next, the determination of an optimal model was done to control the minimal energy consumption, but maintaining the controllable parameters, see Figure 3. In this part, the research explores some optimization techniques to find the optimal control.

The optimal model for the control can focus on minimizing energy consumption, but maintaining the controllable parameters. In this part, the research explores some optimization techniques to find the optimal control, hence the objective function can occur by minimizing the response time, the energy consumption, or maximizing the reliability by means of improving the controller to be more robust. Finally, the model should be compared with similar techniques, analyzing the computational cost of the proposed approach, by including a complete analysis of the system performance against abrupt change, dynamic behavior and some types of faults, incipient or instantaneous, and the % of Total Harmonic Distortion (THD). Additionally, the comparison might follow an analytical strategy of the obtained results through modeling and engineering simulation, using modern tools as big data analysis.

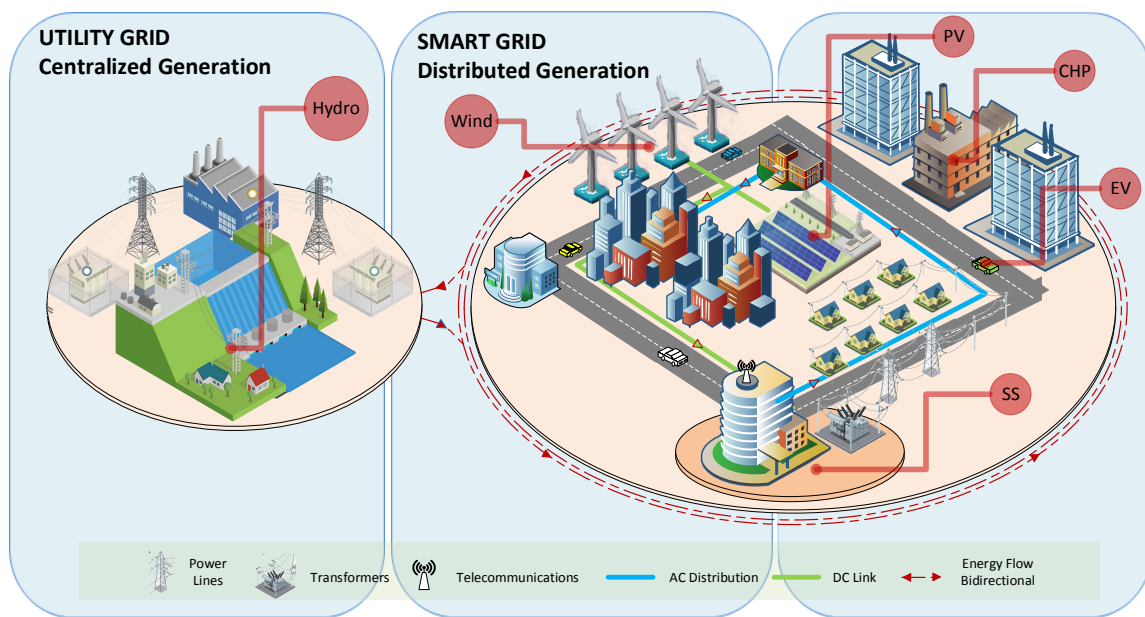


Figure 2. Schematic research showing the SG components.

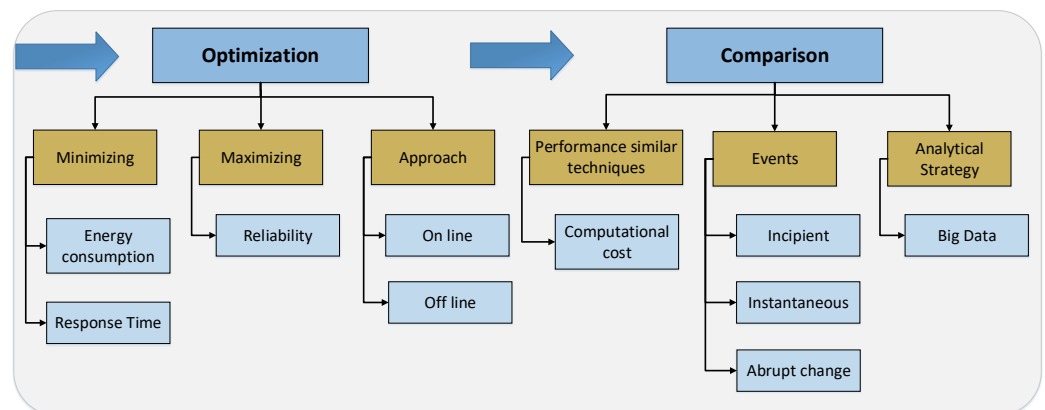


Figure 3. Comparison between a system with centralized and distributed generation.

It is also supposed that the implemented SPSS controllers did not reach an optimal performance due to the following reasons: (a) identification processes were not adequately developed, which allow obtaining the total representation in a mathematical model of the dynamic system behavior, and (b) the optimization techniques were not entirely carried out by applying the controllers, which can be found in the bibliography, comparing the performance among them, and obtaining a quasi or totally optimal controller, considering energy management.

On the point that the methodology is based on the scientific information extracted from the developed SoTA, the section below presents the hypothesis, which is proposed before developing the review. At the end and based on the discussion, it can be concluded whether the hypothesis was true.

- There might be the appropriate and identifiable performance conditions of a SPSS encapsulated in a mathematical model, under which all the dynamic and transient electrical characteristics could be represented.
- It is considered that a SPSS is a non-linear system, thus it could not be represented by identification techniques of classic control theory, for instance, state space can model just a linear system. It is necessary to appeal to more complex control structures, including identification tools like soft computing models to find the complete model

of a SPSS. The quality of the model is determined depending on their ability to model the transient and stable state behavior, including the time variant and dynamic changes of the system.

- There might be control structures, which can be implemented in a SPSS in order to improve its transition stability against different nature perturbation. Additionally, it is assumed that the control can be optimized through algorithms to tackle the control allocation problem and minimize the energy consumption of the entire system.
- It is supposed that there are mechanisms to determine “how good” the algorithms are applied to the optimized controller, and even if they are not the optimal solution, perhaps a local optimal can be found with heuristic techniques.

3. State of the Art

The section below details specific projects and research that have been published in relevant journals in the scientific content to contribute to the proposed problem. The SoTA is divided into relevance and impact in the world and regionally. However, there is a lack of research in the region. Therefore, most research are from other places around the world. SoTA includes models that other researches have used to solve the problem, as well as several methodologies around the field and different models used for solving optimization.

In [1], a review of soft computing models for controlling electrical applications is explored, which includes fuzzy systems, neural computing, evolutionary composition, probabilistic applications, and rough methods. There are several heuristic approaches, among them, adaptive neuro-fuzzy inference system (ANFIS) method, which is a special neural network structure, which improved the basic and can include new patterns through learning. This model is used in [2] for controlling a wind energy conversion systems (WECS) inverter to reduce the disturbance and the % of THD.

Some authors propose software-based solutions for general optimization problems, which are mostly implemented in MATLAB. In [3] is proposed a software framework for nonlinear optimization and optimal control problem (OCP); the program solves constrained problems by differential equations. The last software is called “CasADi”, and it is used by [4] to solve the problems related to OCP, the program mainly improves the solution performance, including discretization time variations.

In [5] is proposed a strategy to evaluate novel coordination methods in smart substation using field programmable gate array, as well as an experimental implementation using hardware in the loop, which can help to demonstrate the actual performance of any practical application.

In MG, there are some innovative techniques to improve their performance. In [6], the authors determine the optimal virtual inertia and the frequency control parameters to preserve the stability landed from the main system of MG. Additionally, [7] explains the procedure to implement the OCP in MG through rolling horizon formulation and models the problem as mixed integer linear programming (MILP), where the final operation cost is the objective function, and the constraints are the physical battery conditions and its charge and discharge process.

Additionally, [8] presents MG trends and the control problems that challenge this novel and spread system type. The problem is that the system output must track its reference values, and the control must ensure that the system oscillations are properly damped in the case of transition between modes of operation.

Additionally, the article divides the control types, including primary and secondary control. The first is in charge of maintaining the electrical parameters in acceptable limits, while the second is the responsible for the economical and reliable grid operation. Finally, the paper discusses the system nature and its features; for instance, in Figure 4, the centralized control enables the implementation of online optimization routines, while the decentralized control coordinated the action of a grid connected system with a MG. Some of the strategies applied in power stations using novel and classical approaches are in Table 1.

Additionally, [9] compares the performances of three different soft computing models, like fuzzy logic controller, static non-linear controller and ANFIS; those methods tested on the control of a variable resistance for fault current limiter VR-FCL. The VR-FCL limits the maximum current in a SG with a different source of renewable energy, such as PV, WECS and synchronous generation.

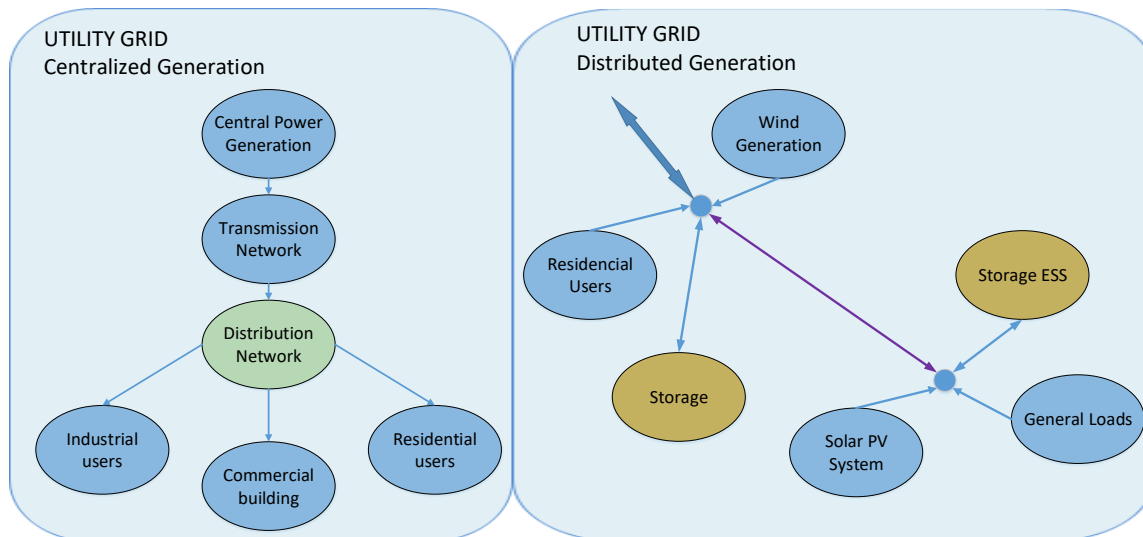


Figure 4. Comparison between a system with centralized and distributed generation.

Table 1. Strategy applied in optimal control.

Approach	Description
Meta-heuristic optimization [10]	Low search efficiency
Mathematical programming [11]	Large computational time
Robust optimization [12]	Uncertainty is not considered
Stochastic optimization [13]	Large amount of scenarios
Model predictive control [14]	Implements rolling horizon iterative
Dynamic programming [15]	Large amount of state and action
Classical controller [16]	Difficult to determine constants
Deep learning [17]	Relies on specific probability

In [18], it is demonstrated that the implementation of distribution automation in DS around the world has improved the reliability and therefore the energy to the costumers. The DS normally presents peaks that depend on the loads and the intermittent and distributed energy resources. The optimization of the model can look for load shedding or shifting and optimize the integration of distributed energy resources [19,20].

Ref. [21] is one of the most referenced books in the field of OCP; particularly, this reference analyzes the weakly coupled systems that have small parameters and cause weak connections. The problem is solved through two methodologies, the recursive and the Hamilton approach, obtaining great performance in controlling the analyzed systems.

In [22], a coordination strategy in the different substation transformers in a DS is proposed, and the problem is defined as a multi-objective optimization. Its objective function is minimizing the bus voltage deviation and the total power loss. The control is implemented in a static var compensator, which is solved with a genetic algorithm with Pareto frontier.

In [23] a load optimal control algorithm is proposed, which improves the model of game theory because it cannot accurately optimize the load control of a SG, instead a load distribution is planned by using clustering to improve the load change rate. The aim of coordination is to improve the reliability in the network and to reduce the cost of energy of

the imported power from the commercial grid. A complete network with the calculation procedure is shown in [24].

There are several MG implemented in the literature, for instance, [25] proposed an MG, which consists of DC and AC buses with different types of loads and distributed generation at two voltage levels. The model was simulated using the MATLAB/Simulink environmental simulation platform.

The solution of any optimization problem can be solved by linear programming. However, due to its complexity, a hard mixed programming level, which is a problem that the computer takes time to solve. There are some authors, among them [26], who present an optimization model based on minimum spanning tree required to deploy phase measurement unit throughout the power system.

In [27], a self-tuning control technique for WECS and hydroelectric plant is presented; those systems have special interest due to their nonlinear dynamic nature, they have stochastic inputs, and the systems typically present excitation and disturbances. Therefore, the paper presents an analysis of the exploded benchmark in the control objectives, and the development of the control solutions, improving reliability and robustness.

The SoTA is shown in Table 2, which describes its discussed thematic, as well as the planned problem including the objective function, means that the problem can be solved using an optimization model, such as minimization or maximization.

Third column describes the constraint that the paper has considered, including its physical constraints, and finally, the implemented methodology to solve the proposed problem.

Figure 5 shows a summary of the topic, which was divided by Table 2. It can be seen that the researches have solved the problem using different methodologies. One of the most used approaches is optimal control, physical constraints, followed by solving optimization and optimal operation. The radial Figure 5 is a tool to decide the steps that a study can follow to find the proper implementation of SPSS.

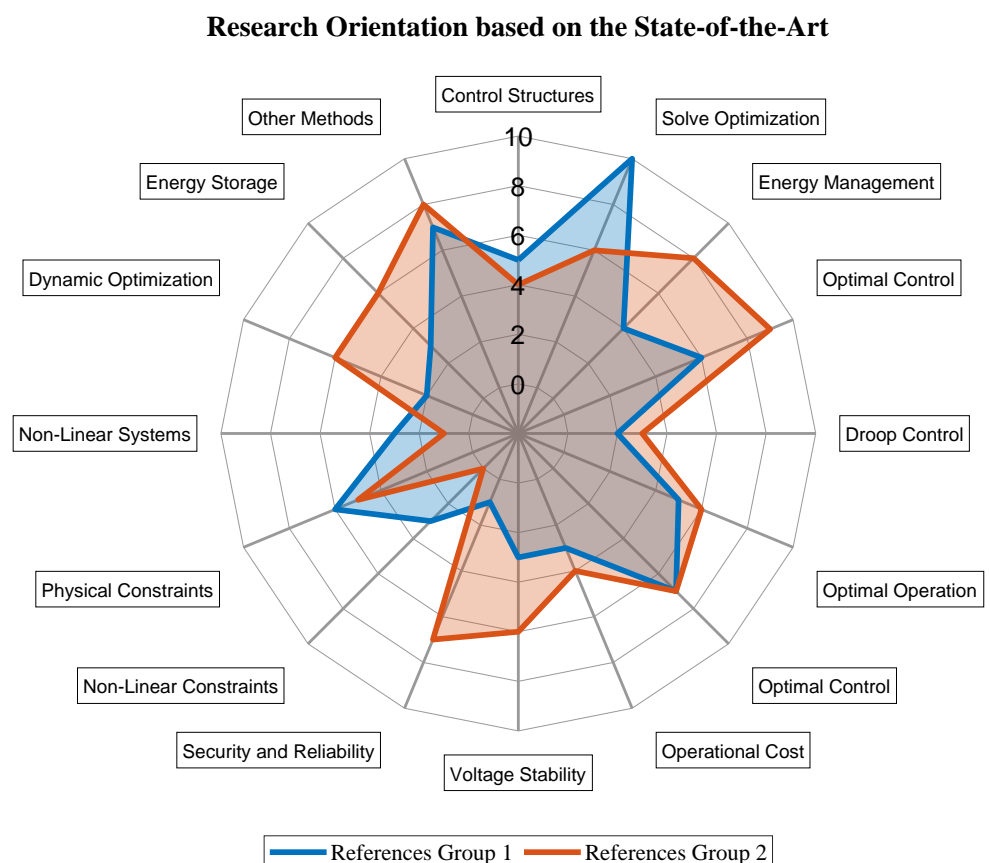


Figure 5. Research orientation based on the state of the art.

Table 2. State of the art optimal control smart substation summary.

Paper	Thematic				Problem				Constraints			Approach				
	Control Structures	Solve Optimization	Energy Management	Optimal Control	Droop Control	Optimal Operation	Optimal Control	Operational Cost	Voltage Stability	Security and Reliable	Non-Linear Constraints	Physical Constraints	Non-Linear Systems	Dynamic Optimization	Energy Storage	Other Methods
Andersson [3]		✘		✘										✘		
Leek [4]		✘		✘										✘		✘
Hajiakbari [6]		✘														✘
Gangl [28]		✘														✘
Olivares [8]	✘	✘	✘	✘	✘	✘	✘			✘		✘			✘	✘
Heymann [7]	✘	✘	✘	✘		✘	✘					✘				✘
Rocabert [29]	✘	✘			✘	✘	✘		✘			✘	✘	✘		✘
Hajimiragha [30]	✘	✘	✘			✘		✘				✘				✘
Bahrani [31]	✘	✘		✘		✘		✘	✘							✘
Kleftakis [32]		✘	✘	✘				✘	✘	✘						✘
Dong [22]		✘		✘					✘			✘				✘
Mirakhorli [33]		✘		✘	✘	✘	✘		✘	✘					✘	✘
Liu [34]	✘		✘		✘			✘	✘	✘					✘	✘
Mhankale [35]	✘		✘	✘	✘	✘			✘	✘					✘	✘
Bao Nguyen [36]		✘	✘	✘		✘	✘			✘		✘		✘		
Wei [37]		✘	✘	✘			✘	✘				✘		✘	✘	✘
Wu [38]	✘	✘	✘	✘			✘	✘				✘	✘		✘	✘
Rahmani [39]		✘	✘	✘		✘		✘		✘		✘		✘	✘	
Dissanayake [40]	✘	✘	✘	✘		✘	✘		✘	✘				✘	✘	✘
Colak [41]			✘	✘		✘	✘		✘	✘				✘	✘	✘

4. Discussion and Analysis

Evolving SG systems compromise the development of modern methods of storing and producing electrical energy, for instance, battery storage, fuel cells, PV, as well as electric vehicles considered as smart appliances plug-in. Consequently, DS through SG has become more elaborated [42] and should transform from a passive, local/limited automation, monitoring and controlled system to an active, self-monitoring, global/integrated, semi-automated system [43].

DS is now an active system that automatically responds to the dynamic behavior of the electric grids. Thus, the DS needs new methodologies to control and monitor the systems, which will result in better efficiency and load management, while the outages would be reduced [37,44].

There are three well-defined SG as follows 1.0, 2.0, and the future 3.0. The first is in charge of the distribution energy automation, Supervision and Control Data Acquisition SCADA systems, advanced metering infrastructure networks, and demand response. The second is known as an advanced SG, which is in charge of distributed energy resource (DER) with renewable generation. Finally, the SG of the future tackled energy trading and roaming.

Substations are part of every electrical generation, transmission, and distribution system, and SG. In the system, the electrical energy flows through substations between the generation plant and the final customer, changing the voltage level in each step [44]. The development of SG profoundly affects the design, construction, and operation of substations [18].

The conventional substation does not satisfy the requirements of the modern power grid [18]. When designing the distribution process it is necessary to consider multiple factors, including reliability and quality of the power supply. Additionally, the designer

must consider parameters like safety, economics, maintainability, operation simplicity, and functionality. Moreover, the substations require a distributed control, protection system, and communication infrastructures [45].

The international standard for substation automation is IEC61850, which contains the general international recommendations for automation implementation in substations that guide the development and trend tendencies of the substation technology [46].

In order to achieve the substation transformation, it is necessary to implement the SPSS, which is composed of a high performance computing platform. The SPSS provides monitoring, protection, control, and communication functions through collecting the data by using time synchronized measurements and high-speed in the substation [47]. The SPSS implements the protection and controls actions within the substation. The protection of the power system against abnormal operation is responsibility of the protection system [47]. This control system supports the operation of the devices with specific program installed in intelligent electric device IED and protection relay [42].

The optimization problem includes the grid components and characteristics related to achieve the required technical constraints with the minimum investment cost [48]. An optimal substation model can consider all the costs associated, which will provide the optimal selection and schedule multistage transformer installations in the substation, taking into account the constraints in the substation system [49,50].

SPSS includes the practical implementation of centralized substation protection and control in SG or MG, depending on the the implemented location. SPSS develops an algorithm to solve the problem of designing a robust control to enhance the best transient performance of a substation, taking into account the electrical variables, and to have the optimal energy management. The algorithm should be designed in a distributed and extensive approach, declaring its limitation and future opportunities, and allowing a dynamic control of the system by considering different fault types, even though related problems are not included, such as fault identification and isolation.

SPSS is shown in Figure 6's model through identification and the optimal control of the system is characterized, including a comparative analysis of the conditions under which the system enhances the transient performance of the electrical variables.

The MG mathematical modeling can be implemented by block diagram, where it is represented by the behavior of each generator and its relationship using lines, feedbacks, forward, and addition points. The entire system can be represented by state space to know the inputs and outputs and their association. Additionally, it is possible to define state variables and characterized their performance. There are several types of MG structures depending on their applications; the technical literature pretends to find an agreement between the model accuracy and simplicity of the representation. [51].

In [52] a hybrid MG is presented, which is shown in Figure 7, but there are differences in the system, for instance WECS, PV, electrolyte generator, and a diesel generator to maintain the frequency in DG. There are two elements to store energy, like a flywheel and a Battery Energy Storage System BESS. The sources are connected to the MG by using appropriate power electronic converter (PEC).

Figure 8 shows how the MG can be represented by a block diagram, and the relationship between the block represents the interchange of power. It is seen that the storage energy devices have a bidirectional power behavior. Meanwhile, each block can be represented by a transfer function depending on the accuracy of the DG model needed, depending on the importance of the source in the system.

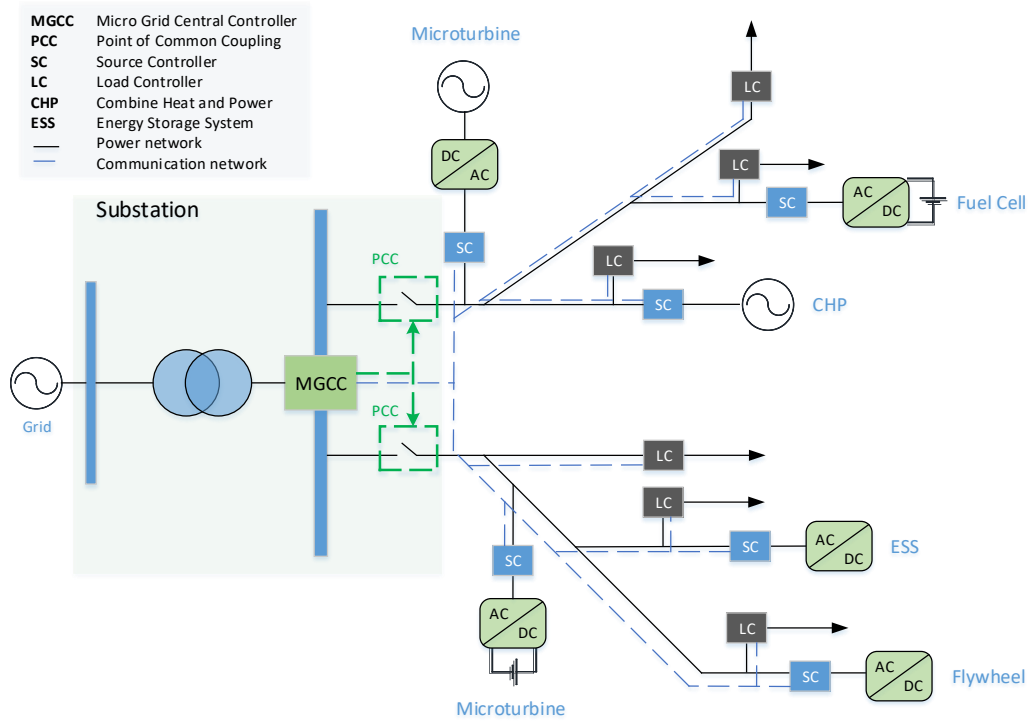


Figure 6. Optimal control strategy in a power smart substation SPSS.

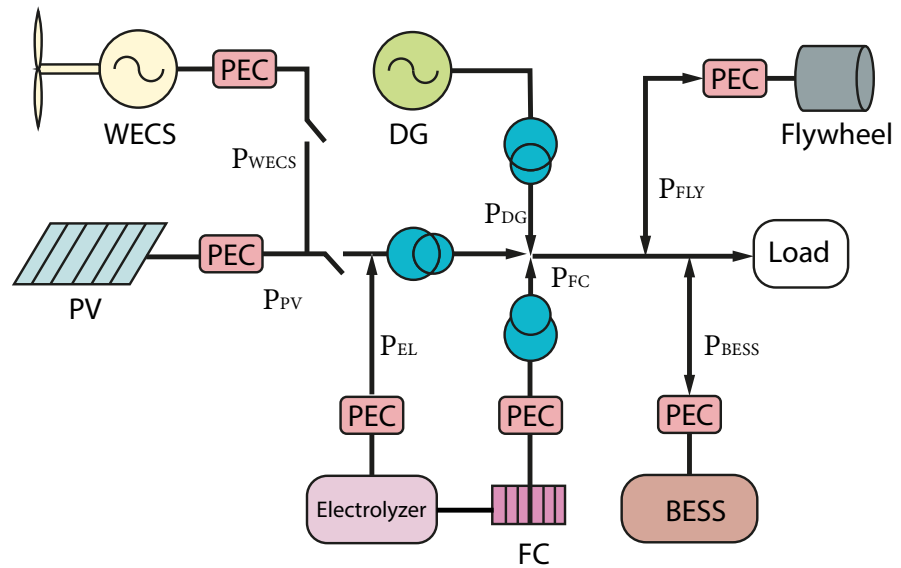


Figure 7. Hybrid MG with different electrical sources.

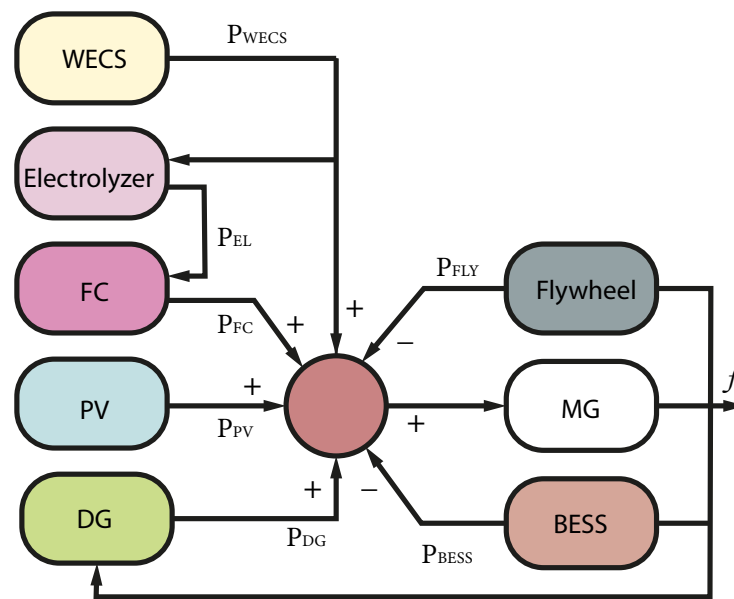


Figure 8. DG representation in a MG by block diagrams and transfer function.

A MG has two operation modes. On one hand, grid connected mode, where the grid provides energy to all the devices in it, in this mode, the control focuses on active and reactive power coordination. On the other hand, it stands alone or isolated, where the challenge is to improve the voltage and frequency quality, ensuring acceptable parameters that allow MG to accomplish the power demand [53].

The PEC operates in two different approaches depending on the MG mode. In the grid connected mode, it tracks the grid voltage, operating as CSI. When the MG is isolated, it works as a voltage source inverter VSI [54].

DER operates isolated, because one or more DER are responsible of regulating the MG voltage. There are different approaches to handle it. The first, master–slave scheme, where one DER in the system works as a VSI, establishing the reference voltage; while the other VSIs track the signal. However, in the case of the master fails, the entire MG can collapse. There is a second option, a multi-master scheme, which coordinates several VSIs in the MG [55].

There are three methods for controlling a MG. Master–slave control is applied to a small MG and it depends on the communication among the PEC. In this structure, the master controls the bus DC voltage and sends the reference signals to the others. Hence, it requires an agile communication network that can reduce the reliability and can increase the system worth [56].

In peer control, there are no masters or slaves, because all the DER is part of the active and reactive power regulation for maintaining the voltage and frequency stability. The droop control belongs to this category, and it does not need DER intercommunication to develop its operation. The proportional load sharing is guaranteed using droop control. The third controller is a mixed between master–slave and peer, and it implies a higher degree of complexity, but gathers the advantages and disadvantages of the two controllers [57].

Hierarchical control coordinates the actions of each controller in a MG, starting in the lower level control to reach the higher level in a central controller [58]. A hierarchical control normally reduces the power variations outside the MG and links the action of the external loops [59].

The primary control implements drop voltage control, voltage, and current control loops, and impedance control, as shown in Figure 9. In addition, this level can include power sharing by implementing P-f and Q-V droop control. The output for the primary level is the deviation values of frequency and amplitude [41]. The reference values for this control are calculated by means of local measurements due to the lacking communication [23].

The current loop objective is to inject a higher gain on the reference signal frequency, to reduce the disturbance effects in the system. Meanwhile, the outer voltage control loop removes the voltage THD, whether there are non-linear loads in the system. The current and voltage loop are crucial in the system final performance [60].

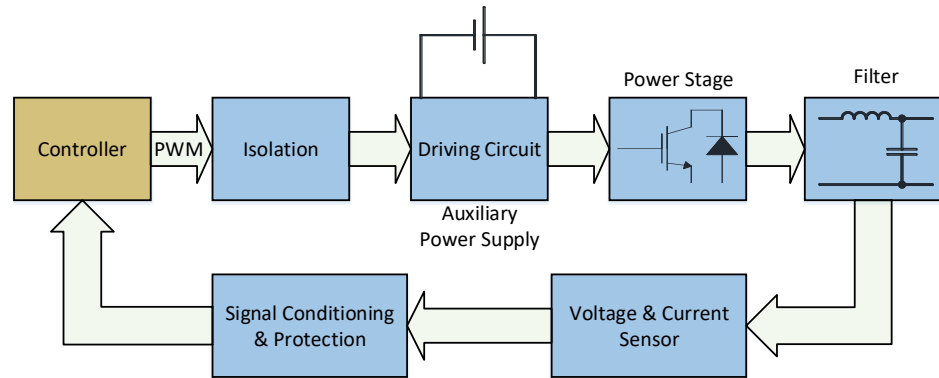


Figure 9. Primary controller in SPSS.

The secondary control regulates the energy flow in the MG, which is calculated for sharing the load demand through the generation and storage elements, as shown in Figure 10. The secondary loop output is a new reference voltage. Therefore, the secondary control ensures the energy balance and accomplishes the quality requirements and operational limits of each device [61].

The tertiary control focuses on energy management by organizing the energy dispatch from the economic and efficient point of view [43].

This optimization process is focused in the minimization of the energy, which will be achieved through the incorporation of certain elements in the control structure that allows the system to implement an online optimization, as shown in Figure 11.

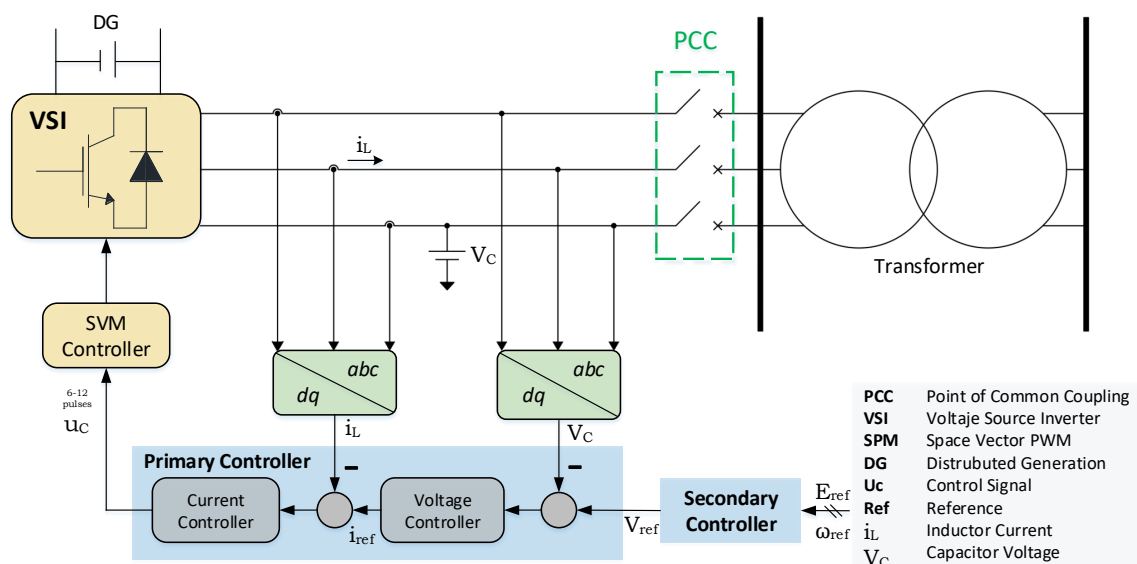


Figure 10. Secondary controller in SPSS.

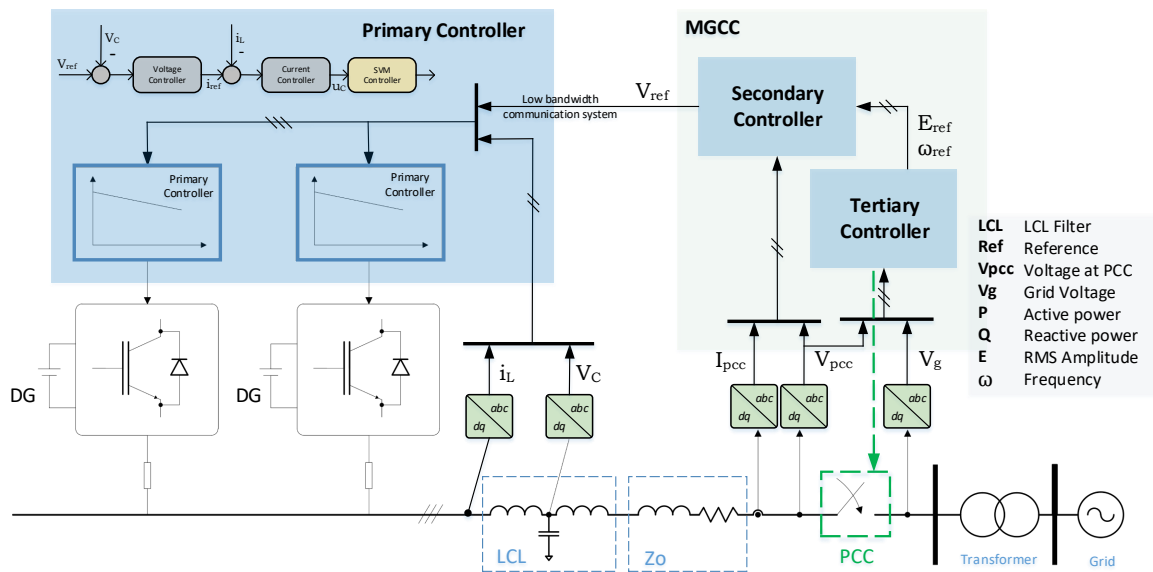


Figure 11. Tertiary controller in SPSS.

The future results of the present research may be extended to others of electrical engineering and other fields applied in control. For instance, the optimal control considering energy consumption can be applied to the controllers of centralized generators, where sometimes the accomplishment of certain electrical parameters is more important than their efficiency.

Moreover, there are specific optimization applications in control techniques in order to find the optimal solution of the control problem, this can be focused in searching the best energy management in the controlled system. Additionally, there are totally identified sub-problems around the main field of the research, for instance the droop control, which is an important obstacle to reach the stability in any DER; the optimal operation, which finds the best option to operate the SG; the optimal control, implemented in SPSS to satisfy all its the technical performances; finally, the cost related with the operation, which is an important concern in the newest engineering technologies.

As far as it is known, there are no current implementations of optimal control applied in SPSS, so it is necessary to conduct future research to see the demonstration of the imperative implementation of this research and the impact of the results in the future, see Figure 12.

It is shown that the SPSS is the principal section in a SG control, thus it should be designed under energy efficiency parameters. Thus, it is supposed that an optimization approach can be applied in an online controller in the system.

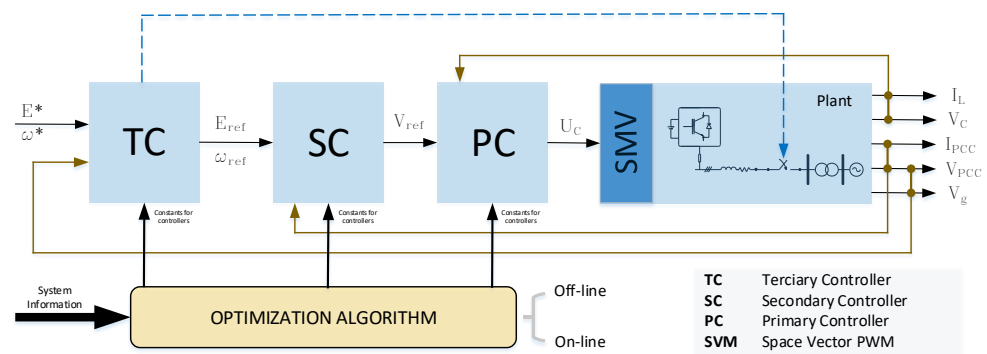


Figure 12. Optimization algorithm in SPSS.

5. Conclusions and Future Works

The author based the proposed method on scientific documents and information extracted from the established state of the art. For this reason, the chosen papers are the most cited and relevant investigations in the fields of electrical power system, power electronics, renewable generation, smart grid, heuristics methodologies, and intelligent control system.

Smart power substations refer to the planned control scheme, which controls the entire system hierarchically. Hence, the hierarchical control appears from the primary controller, which controls the current and the voltage outputs. The secondary control regulates the references for voltage amplitude and frequency, which is based on the expected active and reactive power. Finally, tertiary control deals with energy management and dispatching, which implements a coordination between individual controllers.

In conclusion, smart grid is a fast-growing technology, and this growth implies an enormous demand for better modeling and control. Non-linear behavior and uncertainties represent for control a challenging task to overcome. These considerations drive the lack of advanced modeling and further development of optimal control strategies, with the main aim of maximizing energy efficiency. This renewable energy source could match global electricity demands, especially in rural areas, if it overcomes the technological barriers.

These can also explore similar studies aimed at optimizing the optimal power interchange can be carried out, in particular with other generation, such as wind or hydroelectricity generation. Additionally, different bio-inspired controllers, as fuzzy or neural network, can be explored to improve the nonlinear adaptability. Moreover, the power electronics would develop by exploring different solutions for the new electronic arrangement. They should fulfill a noteworthy validation by testing the proposed power substations in different benchmark systems, first the energy reduction, and the most power point efficiency. Future research will concentrate on a broader analysis, including economical and social fields involved in smart grid.

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