Acta Scientific COMPUTER SCIENCES

Volume 3 Issue 12 December 2021

Research Article

Nonlinear Control of Smart Grids Using PI Controller Modified with Radial Basis Functions

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Received: August 17, 2021

Published: November 12, 2021

Abstract

In this paper, a smart grid modeled with various types of nonlinear loads has been utilized in order to observe the impacts on the nonlinear loads from a disturbance and how to best mitigate the disturbance. We attempted to use multiple Radial Basis Functions to approximate the nonlinear loads and to observe the factors associated with them. A PI controller was implemented in order to control the nonlinear loads.

Keywords: Smart Grid; Nonlinear Loads; Control Strategy for Nonlinear Loads; Radial Basis Function; PI Controller

Introduction

The utilization of nonlinear loads has expanded since the progression of electrical power systems. Such excessive use of nonlinear devices results in a generation of current harmonics and reactive power in the system network. The harmonic current affects the system network performance in several negative sides. Every periodic signal is composed from the sum of sinusoidal signals. Source [1] was used as a basis for this paper.

In order to eliminate or minimize harmonic currents, active power filters can be implemented in the system. In addition to either eliminating or minimizing these harmonics currents, active power filters can also compensate for reactive power in the system. An active power filter functions by first detecting the system's harmonic currents and in-turn calculating the necessary compensation current that would be required in the feedback to the main power system.

A Proportional–Integral (PI) controller was used in order to control the system's voltage. The main principle would be that this controller would compare the reference baseline voltage to the actual system voltage that is being inputted in the system. This would yield the reference's current maximum value as a system output. This would also take the error from the system reference values and actual system values into account.

It compares the reference voltage and the actual voltage thereby giving maximum value of the reference current as output depending on the error from the reference and the actual values. It eliminates the steady state error DC component.

The active filter can be controlled by two methods namely closed loop and open loop. Normally open loop method is easy but less efficient since it measures compensating current to be injected into the network. Hence, we prefer the closed loop operation for precise measurement of resulting current in the network and the active filter injects compensating current in order to minimize it.

Model

Figure 1 shows the active shunt filter (ASF).

Figure 1: Active Shunt Filter Model.

The Active Power Filter's (APF) main function is to supply compensating current from and to the load in order to cancel out the AC side's current harmonics. Another function of the active power filter is to cancel out the reactive power flow from and to the source. Therefore, the source current would be sinusoidal in nature.

The active power filter relies on the method of generating the reference current. The control strategy will generate the gate pulse. The control strategy is comprised of three stages. The crucial voltage and current signals are measured for accurate information during the first stage of the process. The reference compensating currents are derived during the second stage of the process. The solid state devices' gating signals are considered in the third stage of the process. These gating signals are generated using a hysteresis-based pulse-width modulation (PWM) using current control.

Disturbance mitigation

Power outages are classified into three types- permanent fault, brownout, and blackout. A permanent fault is a type of fault with a substantial loss of power. A power line fault is an example of a permanent fault. A voltage drop in the power supply causes a brownout. A blackout, also called a cascading failure, is one of the main causes of power outages. A blackout can either occur from overcurrent or overload. A major improvement regarding disturbance mitigation is the implementation of a self-healing factor. Self-healing transmission systems would minimize power outage time. This system must also provide a balance between generation and customer load demand. Digital power meters could be installed in the residential sectors and commercial/industrial sectors in order to provide an overview of what is happening during power transmission and could predict a potential outage. This information can be analyzed by real-time monitoring systems in order to predict a potential system failure. This system not only could prevent power outages that are caused by environmental factors, but also possible attacks on the smart grid by hacking (cyber security), sabotage, and terrorist attacks.

Figure 2: Three-Phase Fault Circuit.

Various types of three-phase faults can be applied to the following phases: Phase A faults, Phase B faults, and Phase C faults. Fault resistances and ground faults can be introduced into the model.

Battery types

Batteries are available in many different types and capacities. Some popular battery types include Sodium Sulfur (NAS), Vanadium Redox battery (VRB), Zinc Bromide (ZnBr), Lithium Ion (Li Ion), Nickel-Metal Hydride (NiMH), and Nickel-Cadmium (NiCd). This paper will use a lithium-ion battery in the model due to the following reasoning. The Lithium-Ion (Li-Ion) battery has been widely adopted. Lithium-Ion batteries offer multiples advantages over all types of rechargeable batteries. Some of these advantages that apply to lithium-ion include a higher energy density, higher operating voltages, lower self-discharge rate. Lithium-Ion batteries also have some disadvantages that one would need to consider. The main disadvantage of lithium-ion batteries is that they are more expensive than other battery types as they are more costly to manufacture. Some other disadvantages are that they require unique circuity to help protect against overcharging and undercharging, so that the battery does not become damaged during these processes, therefore requiring a specific battery charger to charge these type of batteries. The main system consists of four subsystems. These four subsystems are the energy storage subsystem, power conditioning subsystem, system controller, and the thermal management subsystem. Depending on the system configuration, the energy storage system is the subsystem that consists of the energy storage blocks, electrolyte tanks, and circulation system. The power conditioning subsystem is the subsystem that is responsible for the grid interconnections and inverters and rectifiers that are tied to the grid. Another subsystem is denoted as the system controller subsystem. This subsystem is responsible for the control and management of the main system. In addition to the control and management, this system also provides communication with the other subsystems and also real-time monitoring. The energy management system is a system that manages the charging and discharging settings that the user can configure. Another system, called the thermal management system, manages and preserves the overall system's optimal temperature [9].

In order to model an electric vehicle, a Lithium Ion battery (Li Ion) was chosen for the nonlinear system model. The Lithium-Ion battery parameters are as follows: the nominal voltage is 400 V, the rated current capacity is 40 Ah, and the initial State-of-Charge (SOC) is 100%.

Control strategy for nonlinear loads

In the control strategy, we have divided the controls into four stages. In the first stage, we measured the current flowing in the load. In the second stage, we compared the measured current with the desired current and generate an error signal. In the third stage, we amplified the error signal and generate a correction voltage. In the fourth stage, we modulated the correction voltage onto the load terminals.

Figure 3: Nonlinear Loads Circuit.

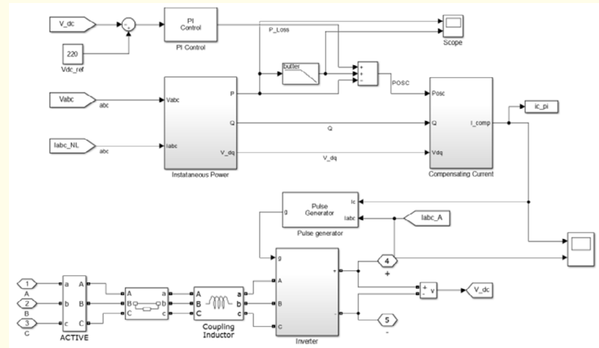

Figure 4: Model with PI Controller.

PI controller

A type of PI controller called the Discrete Proportional–Integral (DPI) controller was implemented. The controller accounts for the reference voltage and the actual voltage. The controller's output is reference current's maximum value. This output is dependent on the reference voltage values and actual voltage values errors. The DC component's steady-state error is either eliminated or minimized [10].

Results

The performance of nonlinear loads has increased since its total harmonic distortion (THD) decreases by using hysteresis and Proportional–Integral (PI) control techniques in shunt active power filter (APF). Developing more efficient control strategies can also mitigate worst case disturbances.

Figure 5 shows the plots of Grid Current, Load Current, and Filter Current. The top graph shows the grid current. The middle graph shows the load current. The bottom graph shows the filter current.

Radial basis functions

A Radial Basis Function (RBF) is a function which is dependent only on the radial distance from a point. RBFs are functions taking on the form where f is a nonlinear activation function, x is the input, and x_i is the ith position, prototype, and basis or center vector.

Figure 5: Plots of Grid Current, Load Current, and Filter Current.

A RBF is a method to approximate a multivariable (multivariate) function based on a single univariate function by using linear combinations of the terms.

RBF is a radially symmetric function that is around a point denoted as x_m. This point is called the dataset function's as stated in equation (1).

$$\sum_{m=1}^{N} w_m \exp(-\gamma \|x_n - x_m\|^2) = y_n$$

------- (1)

Where w_n represents the weights of the centers x_m of dataset (x_n, y_n), while affects the shape of radial basis function.

Calculating Weight of RFB:

$$\underbrace{\begin{bmatrix} \exp(-\gamma\|x_1 - x_1\|^2) & \dots & \exp(-\gamma\|x_1 - x_N\|^2) \\ \exp(-\gamma\|x_2 - x_1\|^2) & \cdots & \exp(-\gamma\|x_2 - x_N\|^2) \\ \vdots & \vdots & \vdots \\ \exp(-\gamma\|x_N - x_1\|^2) & \dots & \exp(-\gamma\|x_N - x_N\|^2) \end{bmatrix}}_{\phi} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_N \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix}$$

------(2)

In the equation (2), the w vector can be found by the following equation (3) if $\boldsymbol{\phi}$ is invertible:

$$W_{n\times 1} = \phi^{-1}{}_{n\times n}\; Y_{n\times 1} \qquad \text{----(3)}$$

This information was used as a basis of the RBF [11,12].

Please refer to references [11,12] for more information on the Radial Basis Function.

Cost function and constraints

Cost function

Maximize power to loads:

Minimum Power ≤ Power generated ≤ Maximum Power

Pmin ≤ P gen ≤ Pmax

$\sum$ P_total = $\sum P_i^n$

Optimize weight to loads:

Minimum Weight allowed ≤ Weight Optimal ≤ Maximum Weight allowed

Wmin ≤ Woptimal ≤ Wmax

$\sum$ W_total = $\sum W_i^n$

Minimize delays to loads:

Minimum Delay allowed ≤ Delay Optimal ≤ Maximum Delay allowed

Dmin ≤ Doptimal ≤ Dmax

$\sum$ D_total = $\sum D_i^n$

Constraints

Subject to

Constraints of Smart Grid (SG) {totals}:

Power of smart grid = Psg

Weight of smart grid = Wsg

Delay of smart grid = Dsg

Constraints due to PV solar panel:

Power of solar panel = Psp

Weight of solar panel = Wsp

Delay of solar panel = Dsp

Constraints due to battery:

Power of solar panel = Psp

Weight of solar panel = Wsp

Delay of solar panel = Dsp

Constraints due to nonlinear loads (RLC):

Power of Resistor = PR

Weight of Resistor = WR

Delay of Resistor = DR

Power of Capacitor = PC

Weight of Capacitor = WC

Delay of Capacitor = DC

Power of Inductor = PL

Weight of Inductor = WL

Delay of Inductor = DL

Constraints due to houses {House 1}:

Power of House 1 = PH1

Weight of House 1 = WH1

Delay of House 1 = DH1

Constraints due to houses {House 2}:

Power of House 2 = PH2

Weight of House 2 = WH2

Delay of House 2 = DH2

Constraints due to houses {House 3}:

Power of House 3 = PH3

Weight of House 3 = WH3

Delay of House 3 = DH3

Constraints due to houses {total}:

Total Power of houses = PHtot = PH1 + PH2 = PH3

Total Weight of houses = WHtot = WH1 = WH2 + WH3

Total Delay of houses = Dtot = DH1 + DH2 + DH3

Constraints due to small factory:

Power of small factory = Psf1

Weight of small factory = Wsf1

Delay of small factory = Dsf1

Constraints due to safety critical location (hospital):

Power of small factory = Phosp

Weight of small factory = Whosp

Delay of small factory = Dhosp

Figure 6: Residential and Industrial Structures as Loads Circuit.

Solar panel

The performance criteria such as power output, energy output, and conversion efficiency determines the amount of PV output. The performance criteria such as power output, energy output, and conversion efficiency determines the amount of photovoltaics (PV) output. Power is denoted in Watts (W). The output power from the PV is the power that is available at the controller or regulator side of the system. It is a measure of how much peak power or average power that can be produced in a given amount of time, for example how much power can be produced in one day. In addition to power, energy is also produced. Energy is denoted as watt-hours (Wh). The output energy from the system refers to the amount o energy produced over a specific time period. The unit of output energy is denoted as watt-hours per square meter (Wh/m^2). This is the sun's radiant energy that is captured by the solar cell. This is sometimes referred to as the power efficiency or conversion efficiency [7].

Solar panel charging battery

Battery storage systems are required in either a smart grid or micro grid type of application. Lead acid batteries were originally used in these applications, but as previously stated in this paper they are not the optimal choice. Lithium Ion batteries are becoming more prevalent in these applications. The battery is one of the most expensive component that is implemented in the system. As the batteries age, one must be aware that battery performance will decrease over time as the battery depends on the Depth of Discharge percentage (DOD %). One must be cognizant not to undersize the batteries that will be implemented in the system. One must also be aware of the battery's "C-rating" during the design phase of the system. The battery's "C-rating" is the battery's ability to provide the safe maximum amount of current that the system can extract from the battery while still provide sufficient backup power to the smart grid or micro grid system in addition to mitigating damage to the infrastructure [7].

The primary function of any battery management system (BMS) is to manage the battery's observable parameters and variables, such as the cell voltages, cell currents, cell temperatures, and also the battery state-of-X (SOX) functions. SOX functions are the battery's state-of-charge (SOC) and state-of-health (SOH), but can also include the battery's state-of-power (SOP) and state-of-function (SOF) parameters as well. Depending on the complexity of the BMS, the system can also include additional features such as type of fault detection and/or fault diagnosis, cell balancing, among other parameters. Kalman filtering can also be implemented for state estimation and to help improve the overall optimal control strategy that the BMS could use in order to better determine the power that is being commanded from and utilized in the system [8,9]. Also, model predictive control (MPC) and/or model predictive estimation (MPE) could also be employed to benefit the system's performance.

Figure 7: Direct Coupled Solar PV System [7].

Figure 8: Block diagram of Standalone PV System with Battery Storage [7].

Conclusion

Overall, the nonlinear loads performance increased and therefore improved. This was accomplished by decreasing the THD using hysteresis and the PI controller in the shunt APF. Other control strategies that could help mitigate the worst case disturbances could include Proportional-Integral-Derivative (PID), Linear–Quadratic Regulator (LQR), or some type of Model Predictive Control (MPC). The Model Predictive Control (MPC) and Model Predictive Estimation (MPE) would be explored in a future paper regarding the charging of an electric vehicle (EV), more precisely a Plug-in

Hybrid Electric Vehicle (PHEV). The charging system equipment would be a Level 2 AC electric vehicle supply equipment (EVSE) charging station.

Bibliography

1. Seyed Ali Arefifar., *et al*. "Comprehensive Operational Planning Framework for Self-Healing Control Actions in Smart Distribution Grids". *IEEE Transactions on Power Systems* 28.4 (2013).
2. Seyed Ali Arefifar., *et al*. "Energy Management in Multi-Microgrid Systems- Development and Assessment". *IEEE Transactions on Power Systems* 2.2 (2017).
3. U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability by the National Energy Technology Laboratory, September (2009).
4. Xi Fang., *et al*. "Smart Grid- The New and Improved Power Grid: A Survey". *IEEE Communications Surveys and Tutorials* 14.4 (2012).
5. Hamid Reza Baghaee., *et al*. "Nonlinear Load Sharing and Voltage Compensation of Microgrids Based on Harmonic Power-Flow Calculations Using Radial Basis Function Neural Networks". *IEEE Systems Journal* PP 99 (2017).
6. Garima Goswami and Pankaj Kumar Goswami. "Simulation of Power Quality Control of Non Linear Load Using Fuzzy Controller at MATLAB". *International Journal for Research in Science and Advanced Technologies* 3.2 (2013): 114-119.
7. S Sumathi., *et al*. "Solar PV and Wind Energy Systems: An Introduction to Theory, Modeling with MATLAB/SIMULINK, and the Role of Soft Computing Techniques". Chapter 2, Springer International Publishing, Switzerland (2015).
8. Jaw-Kuen Shiau and Chien-Wei Ma. "Li-Ion Battery Charging with a Buck-Boost Power Converter for a Solar Powered Battery Management System". Department of Aerospace Engineering, Tamkang University, *Energies* 6 (2013): 1669-1699.
9. Priety and Vijay Kumar Garg. "To Perform MATALB Simulation of Battery Charging Using Solar Power With Maximum Power Point Tracking (MPPT)". M. tech Student (EE), UIET, Kurukshetra University, Kurukshetra, Haryana, India, UIET, Kurukshetra University, Kurukshetra, Haryana, India, *International Journal of Electrical Engineering* 7.5 (2014): 511-516.
10. R Arun., *et al*. "Shunt active power filter using Hysteresis and PI Control for improving the power quality using MATLAB". Green Engineering and Technologies (ICGET), 2015 Online International Conference, 27-27 Nov. (2015).
11. M Barnard., *et al*. "Speech Enhancement and Recognition Using Kalman Filter Modified via Radial Basis Function". *International Journal of Computer and Information Technology (IJCIT)* 9.2 (2020).
12. M Barnard and M Zohdy. "Continuous Speech and Time-Frequency Transform Using the Kalman Filter". *International Journal of Computer and Information Technology (IJCIT)* 9.2 (2020).

Volume 3 Issue 12 December 2021