❒ 1268

Nonlinear control of GTI for stabilizing future smart grids

Salam Ibrahim Khather
Department of Systems and Control Engineering, Ninevah University, Iraq

Article Info

ABSTRACT

The most important components of the distributed generation frameworks is the GTIs which is an interface amidst the utility and the source of energy. The recent years have seen an increased interest in the design and usage of GTIs due to its smaller weight and size, low cost and higher efficiency. But the problem of leakage currents in the transformerless inverter that is dependant on its topology and control scheme needs to be looked into carefully. Also, the high performance of the GTI requires a stringent control and various control systems are being developed and applied to the GTIs. This paper reviews the various topologies that are classified based on the attributes of the leakage current and the method of decoupling. Further it reviews and compares the different control techniques applied to the GTIs with respect to the frame of reference, controller, modulation technique and the control parameters considered.

Corresponding Author:

Salam Ibrahim Khather,
Systems and Control Engineering Department,
Ninevah University, Ninevah, Mosul, Iraq.
Email: salam.khather@uoninevah.edu.iq

1. INTRODUCTION

The traditional systems that use coal, nuclear and hydro energy for generating electricity are centralized and need the transmission of electricity over large distances. The stability and security of these systems are under threat due to the blackouts which is a result of grid rupture due to extreme weather conditions, chain failure. In comparison, the distributed sources of energy like biogas, biomass, wind and solar are decentralized, flexible and modular. These sources of energy have an added advantage that they can be produced close to the place of consumption [1]. Also, the environmental concerns like the climatic changes and global warming are driving the requirement for penetrating the distributed renewable sources of energy into the future generations of electricity grids. The attributes of electricity generation and supply are being changed with the aid of generating and storing electricity in an environment-friendly manner. Hence the microgrids are a unique solution for integration of the renewable sources of energy into the distribution systems [2]. The microgrids, specifically the ones using wind and solar energy have accomplished immense response over the recent years for meeting the energy demands of the world and have become a significant alternative to the conventional sources of power [3].

Implementing the microgrids is advantageous to both the consumer as well as the electricity provider. From the consumer's point of view, the microgrid enhances the quality of the network, decreases the emissions, and cost they incur. From the perspective of the electricity provider the microgrids aid in the reduction of the power that flows on the transmitting and the distributing lines which results in the reduced costs and losses for extra power [4]. Additionally, the microgrid also helps in reducing the load on the network by the elimination of impasse to meet the requirements of electricity and repairing the network in the case of any errors. The microgrids are the smaller versions of the actual electricity distribution systems.

They along with reducing the impacts on the environment by increasing the use of renewable resources have the ability to enhance the economics, network reliability and quality of the power. From the perspective of operation, the microgrid consists of power electronic control and interface circuit for meeting the requirements of quality of the power, flexibility factor, and the energy output [5].

Conversion of the power among DC and AC is a primary issue in the microgrids since the renewable sources of energy generate DC power whereas the traditional electricity grid is dependant of generating, transmitting and distributing AC power. Hence there is a need for converting the DC power to AC power so that the grids can be connected to the standard AC system. The circuits of power electronics are utilised as an inverter for the DC to AC power conversion. There are numerous types of such inverters and they are referred to as grid-tied inverters (GTI). The grid tie inverter is the same as that of a DC-AC converter but with a slight difference in the characteristics. The GTI needs to obey certain conditions without which it cannot be connected to the grid. The magnitude of the phase and voltage of the GTI must be equal to that of the grid, the inverter output frequency and the frequency of the grid must be equal [6].

2. TOPOLOGIES OF GRID-TIED INVERTERS

In spite of the development of various GTI topologies, most of them can be classified into three groups of zero-state decouple, zero-state mid-point clamped, and solidity clamped topologies. These classes are decided based on the characteristics of leakage current and the decoupling approach of the transformerless topologies. Each of these classes is discussed below.

2.1. Zero state decoupled transformerless topologies

The traditional full bridge topology has various features for operating in single phase connected to a simple PV module like the structure of the circuit, low DC bus voltage, high efficiency, low cost in comparison to the half-bridge topology. Various full bridge topologies have been developed by decoupling the PV module from the grid during the period of freewheeling. The studies related to zero state coupling are further discussed.

Yang et al., [7] developed an enhanced single-phase inverter for eliminating the common mode leakage current in the transformerless PV grid system. Both the control techniques of double-frequency SPWM and unipolar SPWM were implemented to obtain a three level output for the inverter that assures that the common-mode leakage current is not generated. In the commutating switches, their switching voltages are 50% of the input voltage and the losses due to switching were reduced significantly. Addition decoupling of two switches in the inverter helped in accomplishing high effectivity and feasible thermal design. Lower ripples in the current and higher frequency were achieved due to double-frequency SPWM. The authors in [8] developed a high reliability and efficiency (HRE) topology utilising the MOSFETs to be the main switches. The proposed converter used two split ac-coupled inductors which operated solitarily for the negative and positive half cycles of the grid. The circuit did not require dead time for commutating at PWM switching hence achieved a lower distortion for the output current. This topology is an attractive option for the applications that require transformerless PV inverters.

Yu et al., [9] developed a high-efficiency H6 configuration inverter utilizing MOSFETs. The developed topology featured high-efficiency over a broad range of the load, low leakage current in the ground and no requirement for split capacitors. The output inductance was reduced by 50% in comparison to the full bridge inverter that uses bipolar PWM switching. In [10] the study summarized the derivation rules from the present inverters having high performance using H6 configuration so that novel topologies are achievable. As an example, the authors developed a high efficiency 1ϕ transformerless PV inverter with a hybrid modulation technique. the absence input split capacitors eliminated the issues of leakage current and common-mode voltage in the nonisolated model with H6-type configuration. They additionally proved that the H5 topology is a variant of H6 topology. The main demerit of these topologies was the activation of the anti-parallel diodes of MOSFETs due to the occurrence of a phase shift between the output current and voltage of the inverter. As a result, the issue of low reverse recovery in the anti-parallel diodes of the MOSFETs reduces the dependability of the system. The authors in [11] presented a detailed review, analysis and classification of the single-phase FB inverter topologies that did not face the problem of leakage current. Based on the elimination of the CM mode voltage these topologies H4, H5, and H6 were bifurcated as inverters with decoupling and inverters with clamping. Among the clamped inverters they analysed one topology to validate its efficiency by developing the prototype. The developed inverter prototype gave an efficiency of 98.5%. The study in [12] presented an improved form of H5 topology for reducing the CM leakage current. Effective differential mode attributes were obtained for the three-level output voltage since they employed the unipolar SPWM control technique. The grid-connected current had low THD and high

current. This inverter obtained a maximum efficiency of 98.2% making suitable for grid-connected applications.

2.1. Zero-state mid-point clamped transformerless topologies

This topology is similar to the previous one with the only difference that the output voltage which is short-circuited is during the period of freewheeling will be clamped to DC bus mid-point. As a result, the CM voltage is maintained at a constant value during the complete period of operation. Most of the mid-point topologies can be obtained from the decoupled topologies. The authors of [13] developed an optimised H5 topology (oH5) in which the CM voltage is clamped at a constant level so the ground current voltage is suppressed. The H5 circuit is modified by adding the clamping branch that comprises of the capacitor divider and a switch. But this circuit requires the addition of a dead time amid the gate signals for avoiding the short-circuiting at the input split capacitor. Also, the losses due to conduction are high since the inductor current flows through all the switches when they are in active mode. The study [14] developed a new topology based on the H-bridge with an AC bypass circuit that comprised of a switch that was clamped to the midpoint of DC and diode rectifier. The use of unipolar PWM for modulating the switches gives a three level output to the converter hence, the generated CM voltage had high-frequency components resulting in high leakage currents at the ground. The authors in [15] introduced two types of switching negative and positive neutral point clamping to develop an NPC topology referred to as PN-NPC topology. Its principle of working is similar to H6 topology. At the time of freewheeling the short circuit output voltage is clamped directly to 50% of the input DC voltage due to which the CM voltage remains constant. But the main demerit of this topology is the higher number of switches which increases the complexity of the circuit. Also, the losses due to conduction are higher.

2.3. Solidity clamped transformerless topologies

In these topologies, one can observe a solid connection among the grid and the PV module in the freewheeling mode with an aim to maintain the CM voltages at high frequencies. Although the common characteristic of the topologies is the solid connection, the principle of operation, boosting, DC bus and the characteristics of the output voltage can be different. The research work in [16] developed a solidity clamped transformerless topology referred to as a dual parallel buck converter. For this topology there exists a direct connection amidst the PV module and the neutral inverter during both the positive as well as the negative half cycle thus reducing the oscillations of the high frequency CM voltages. The losses due to conduction are also reduced since the inductor current flows through only two switches. The study in [17] developed the concept of virtual DC bus for eliminating the CM leakage current in the transformerless PV models. There exists a direct connection between the grid neutral and the Dc bus negative pole thus bypassing the stray capacitance that is present between the ground and the PV panels. Hence the CM leakage current is suppressed completely. In the meantime, a virtual DC bus gets created for providing the negative voltage level for the negative AC grid for generating the current. Thus the DC bus voltage required is the same as that of the FB inverter. But it is difficult to control the charging of the virtual capacitor at each of the cycles and the additional current stresses affect the switches, resulting in reduced reliability and efficiency. The researchers in [18] developed a positive-negative NPC (PN-NPC) topology for effectively eliminating the leakage current. The two basic switching cells, the P-NPCC, and the N-NPCC are developed for generating the GTI topology to build NPC topologies. The main advantages of this approach are that the CM voltage is clamped at a particular level for effectively suppressing the leakage current, excellent DM mode attributes are achieved. The requirement of a deadtime is the main demerit of this topology without which there will be a short circuit in the grid [19].

3. CONTROL OF GRID TIE INVERTERS

There is a requirement of a control system for guaranteeing the high quality of power. The harmonics for the nonlinear load which is drawn from the grid, the difference in phase between the current and voltage need to be compensated with the aid of inductor and capacitor as the loads. To accomplish the current at the output of the inverter, load current, grid current, or the current at any of the nodes can be controlled. Below discussed are some of the controllers based on their applications.

3.1. Linear controllers

These controllers are a part of the class that features the attributes of the linear systems. The linear controllers are designed and evaluated using the traditional theory of feedback control. A linear classic controller for distributed generation (DG) inverters under the influence of voltage sags was developed in [20]. The control depends on reactive current injection wherein there is a variable ratio amidst the negative

and positive sequences. This controller aids in restoring the dropped voltages during the limits of continuous operation determined by the grid. A unified control technique enabling the operation of the DG inverters in both grid-tied as well as islanded modes without the requirement of switching among the corresponding controllers was developed in [21]. The inverter is controlled as a current source using the inner current loop of the inductor in the case of grid-tied operation and when the islanding occurs the voltage controller is automatically gets activated in order to control the load. This technique was successful in improving the quality of waveform of the grid current in grid-tied mode and the islanded mode load voltage.

A current controller without PLL that is applicable for PV systems. The developed controller is a combination of the linear-quadratic regulator (LQR) and the Kalman filter referred to as LQG controller was developed [22]. This controller made sure that the balanced and sinusoidal currents are injected with high immunity for both harmonics as well as the imbalances which are existing in the supply voltage. This is accomplished without a PLL for synchronisation of the grid voltages and the currents. A novel approach for controlling the reactive and active power of the 1Φ rooftop PV module was presented in [23]. Estimation dependant improved PLL was employed for locking the grid and the inverter with each other. The stability of the controller was analysed utilizing the Direct Method of Lyapunov's Stability Criterion. It was observed that the controller performed well even though the harmonic compensator was absent. The authors in [24] introduced an active damping (AD) technique depending on the injected feedback grid current for the GTI that employs LCL filters. The resonance at the LCL filter is rejected by the phase shifting and high pass feedback for the injected current at the grid. Contrasted with the conventional control techniques, besides avoiding additional high-accuracy sensors and perceptions, the proposed control is alluring for both the high closed-loop transfer speed and the great robustness.

3.2. Robust controllers

The main theory behind these is to design the controllers with respect to uncertainties. The objective of these strategies is to accomplish robust execution and stability within the sight of constrained modelling errors. In robust control, great criteria, clear portrayals, and limits must be characterized. Indeed, even in the multivariable frameworks, this controller can assure robust steadiness and execution of closed loop frameworks. Figure 1 illustrates the structure of a basic controller.
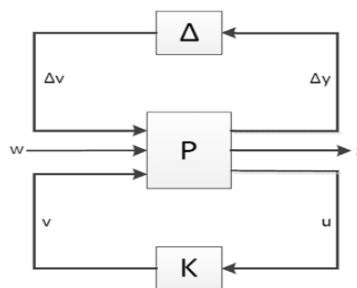

Figure 1. Robust controller [25]

A current controller based on the H∞ control theory was designed in [26]. The controller has a stabilizing compensator which can be just an inductor. This results in enhanced tracking performance and a low value of THD even when the unbalanced or nonlinear loads and distortions in the grid voltages are present. To achieve this slight compromise was made with respect to slower dynamics with more complicated calculations. The study in [27] also developed a H∞ controller for dealing with the issue of stability. The controller exhibited high gains near the high frequency lines just like the conventional proportional resonant controller. It also has optimum attenuation at high-frequency to maintain the stability of the control loop. The results of both the experiment and simulations of the proposed H∞ controller and the ordinary PI controller were compared for validating the performance of the controller. It ought to be noted that the proposed H∞ controller can be effectively connected to single-stage GTI since it is created in the stationary frame of reference. The study in [25] developed a robust current controller for a 3Φ GTI that offered better performance for tracking and higher ability to reject the harmonics when compared to the conventional PI controller. The authors used the Mu-synthesis technique for considering the effects of unstructured as well as structured uncertainties on the system performance. Here the nonlinear expressions were included by modifying the disturbance scaling parameter and the uncertainty model for better

simulation in the realistic. The low pass filter was modified to a higher order system which helped in attaining a higher rate of rejecting the harmonics.

3.3. Adaptive controller

Versatile control techniques as shown in Figure 2 can naturally modify the control activity relying upon the working states of the framework. There is no compelling reason to know the exact framework parameters with high performance. But the complexity of computations in this approach is very high.
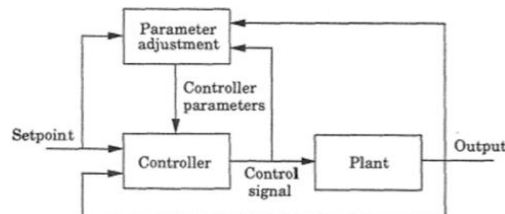

Figure 2. Generalised structure of an adaptive controller [28]

The study in [29] assessed the conduct of an adaptive current controller that is based on a generalized integrator of reduced order when the frequency of the grid is subjected to the variations. The proposed plan for frequency adaptation permits to keep the good performance of the present controller even within the sight of variations in the frequency. The subsequent frequency adaptive controller has extremely low computational weight, and it is hence feasible for low cost DSP execution. An adaptive controller for 3Φ stand-alone DGs was developed [30]. For preventing the direct calculation of the derivatives of time for state variables by developing the adaptive compensating control and the error dynamics in the model is asymptotically stabilized using the stabilizing control. An optimal observer of the fourth order estimated the data about load current. The stability of the developed observer and controller was scientifically demonstrated by applying Lyapunov stability hypothesis. This versatile control technique accomplished more stable yield voltage and lower THD than the FL-MIMO control plot under abrupt change in load, uneven and nonlinear load. The viability and possibility of the proposed control system were confirmed through different simulation and trial results.

An adaptive controller for a 3Φ inverter that can be applied to a UPS was described in [31]. The control law, that employed the integration of state feedback and tracking error is portrayed in a synchronous dq outline and is actualized utilizing a space vector modulation system. The controller is structured by a linear matrix inequality (LMI) based streamlining with the goal that the rate of convergence for the steady state is expanded within the sight of the LC filter vulnerabilities. In the absence of uncertainties, the designed controller will become a deadbeat controller, whereas, in the presence of uncertainty, it provides the shortest possible settling time. Thus, the proposed design method provides a systematic tool to combine the robustness to model uncertainties with deadbeat control. Along these lines, the proposed technique gives a methodical apparatus to join the strength to display uncertainties with the deadbeat control. A droop control method that estimated the impedance and controlled the adaptive virtual power was developed in [32]. The online estimation is acknowledged by delivering a perturbation on the magnitude of the voltage and estimating the power output variations and afterwards, the impedance highlight can be determined to update the conversion matrix of the virtual power. This technique is appropriate for various conditions of working and different line X/R proportions. By considering both the impacts of the loads as well as the transmission line, the decoupling framework is progressively functional and improves the power control precision. An adaptive voltage control approach by combining the adoption and a state feedback control terms was developed in [33]. The former helps in compensating the uncertainties of the system and the later forces the convergence of error dynamics to zero. Additionally, the developed algorithm can be implemented easily. The simulation and exploratory outcomes were exhibited under the uncertainties of the parameter and are contrasted with the exhibitions of the non adaptive voltage controller to approve the adequacy of the proposed control technique. Without uncertainties, an adaptive controller will turn into a deadbeat controller, but when the uncertainties are present, it gives the briefest conceivable settling time.

3.4. Predictive controllers

Predictive controllers as shown in Figure 3 utilize a framework model to foresee what's to come in the conduct of controlled parameters. The controller utilizes this data to get the ideal activation, contingent

upon a predefined optimization measure. With its quick unique reaction, nonlinearities, and limitations which can be effectively included and it can be applied to various systems while considering a multivariable case, moreover, the execution of this controller is simple. The authors in [34] modelled and designed the discrete-time hybrid current controller which was a combination of PI and repetitive parts. Additional passive filters were connected between the transformer and the converter terminals to ensure that the converter synthesised the sinusoidal currents. But these filters have the ability to cause issues pertaining to harmonic resonances. The authors in [35] digitally implemented a control system considering the imbalance in grid voltage, imbalance as well as the harmonics of the inductors on the line side. The direct technique of Lyapunov ensured its stability. Contrasted with a work of classic controller, this controller requires an incredible number of calculations.
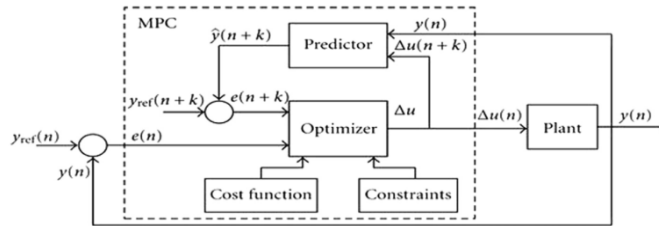

Figure 3. The predictive controller [36]

3.5. Intelligent controllers

Intelligent control gets computerization by imitating biological intelligence. Likewise, it investigates to obtain thought from the way biological frameworks make sense of issues and uses them for solving the control issue [37]. The design of a repetitive controller (RC) applied to an LCL filter based GTI was presented in [38] with a particular emphasis on the bandwidth of the plant. The results indicated that correct selection of the capacitor value in the filter would provide the appropriate bandwidth for the effective operation of the RC. It was also observed that the RC effectively handled the higher resonance for the chosen value of the capacitor. The parallel structure for fractional RC technique for enhancing the performance of the inverter was developed in [39]. A correction factor is incorporated to increase the gains of all the harmonics precisely at the harmonic frequencies which have been targeted. This technique accomplished better rejection and tracking in comparison to the conventional RC. In [40] the authors developed a frequency adaptive repetitive control scheme (FARC) wherein the rate of sampling was already defined for dealing with the various kinds of variable frequency periodic signals. This FARC controller offers the quick modification of the process of fractional delay, and quick reexamine of channel parameters, and after that gives GTI a basic yet very exact continuous recurrence versatile control answer for the infusion of high calibre sinusoidal current. The general form of a repetitive controller as shown in Figure 4.
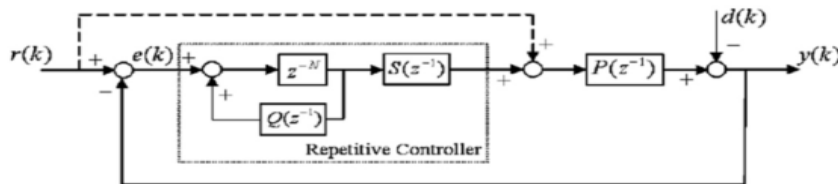

Figure 4. The general form of a repetitive controller [41]

3.6. Nonlinear controllers

The non-linear controllers [42] operate extraordinarily when compared to the basic controllers but are complex with respect to the aspects of designing and implementing. The nonlinear controllers can be grouped into three types the Sliding mode controllers [43], PFL controllers and Hysteresis controllers [44]. These controllers are discussed in detail in the next section.

4.   TYPES OF NONLINEAR CONTROLLERS

4.1. Sliding mode controllers (SMC)

This method has been applied to the PWM inverters for regulating the output voltage. The main merits of this technique are its insensitivity to the disturbances in the load and variations of the parameters. Hence for the ideal case, an invariant steady-state response is obtained. But finding an easy sliding surface is a difficult task and the limited sampling rate degrades the performance of the SMC. The phenomenon of chattering is another demerit of the SMC when a variable reference is tracked. The authors of [45] presented an SMC through a multi-resonant sliding surface for a 1Φ GTI for eliminating the error in tracking the grid current and suppressing the THD. To accomplish this completely many terms for error of current tracking are added with the sliding function. This technique can be employed in arbitrary tracking in an AC system. A novel SMC for a DG system when there exists a condition of distorted grid was developed [46]. This controller has a SMC current controller and one harmonic detector. The SMC is based on the control of the integral sliding mode. Effective extraction, without any phase delay, of the harmonic components is achieved by using a band pass filter of the fourth order. The SMC suppresses these harmonics with a fast dynamic response. This is a harmonic compensation scheme that is non-selective, hence reducing the burden due to the computations.

4.2. PFL controllers

A clear route for structuring the nonlinear controllers is feedback linearization since it changes a nonlinear framework to a halfway linear or a completely linear framework. This can be accomplished by eliminating the nonlinearities inside the framework. Along these lines, linear controller structure techniques can be utilized to structure the controller for these frameworks. At the point when the nonlinear framework is changed into a completely linear framework, the technique is referred to as exact feedback linearization and if the nonlinear framework is changed into an in a partial linear framework, the strategy is called partial feedback linearization (PFL) [47].

An effective nonlinear controller for a 3Φ GTI for controlling the injected current and voltage at the DC link so that maximum power could be extracted from the PV units was designed in [48]. The technique was based on the PFL and effectiveness was ensured by the consideration of the uncertainties in the PV system. The results indicated the excellent performance of the controller under different conditions of operation. The study in [49] presented a controller for controlling the 1Φ GTI having non-linear loads by the addition of the load current to the current loop of the inductor filter. The GTI is stable in both modes of standalone and grid-connected. The results from the simulations indicate that the in the grid connected mode the current is eliminated and quality of the output voltage waveform is high in the stand-alone situation.

4.3. Hysteresis controllers

It is worth referencing that for executing the hysteresis controller, a versatile band of the controller needs to be designed to accomplish a constant switching frequency. Contemplations in regards to the disengaged neutral are significant once more, in light of the fact that the yield of this controller is the state of the switches. The authors in [50] developed a multiple-resonant SMC (MRSMC) along with a variable-band hysteretic modulator (VHM) for a 3Φ GTI. The VHM eliminates the chattering issue of the SMC. In comparison to the SMC the designed controller is superior with respect to the higher order harmonic injection to the grid. The hysteresis current controller for a 3Φ GTI with reduced losses was designed in [51].

Table 1. A comparison of the controllers in the existing literature

Reference	Reference frame	Controller	Control parameter	Modulation technique
[26]	3Φ, d-q	Robust (H∞)	Current	PWM
[30]	3Φ, d-q	Adaptive	Voltage	SVPWM
[52]	1Φ	Non-linear (Hysteresis)	Current	PWM
[53]	1Φ	Non-linear (Hysteresis)	Current	PWM
[32]	3Φ, d-q	Adaptive	Power	PWM
[20]	3Φ, αβ	Linear (Classic)	Voltage, Power	PWM
[23]	3Φ, αβ	Linear (PR)	Current	SVM
[54]	3Φ, d-q	Non-linear (SMC)	Current	PWM
[33]	3Φ, d-q	Adaptive	Voltage	SVPWM
[55]	1Φ	Non-linear (SMC)	Current	PWM
[48]	3Φ, d-q	Non-linear (PFL)	Voltage, Power	PWM
[34]	3Φ, d-q	Predictive	Current	SVM
[56]	3Φ, abc	Intelligent (fuzzy)	Power	PWM
[39]	1Φ	Intelligent (repetitive)	Voltage	PWM
[57]	1Φ	Intelligent (repetitive)	Current	PWM
[58]	3Φ, αβ	Non-linear (Hysteresis)	Current	PWM

The negative or positive buses are clamped to the inverter based on the phase current polarity. Hence all the phases of the inverter get clamped for ⅓rd of the output period. The clamping process helped in reducing the average switching losses and frequency. The results indicated that the developed controller has the ability to decrease the losses of switching without compromising on the waveform of the output current. A comparison of the controllers in the existing literature as shown in Table 1.

5. CONCLUSION

It can be observed that various studies have been conducted on GTIs based on the inverter topology and controller for the inverter. The inverter was classified into three basic topologies based on decoupling and characteristics of the leakage currents. Each of the topologies has its own merits and demerits, hence it cannot be concluded as to which topology is the best. For selecting a particular topology factors like cost, efficiency, leakage current and the number of power semiconductor devices need to be considered. Further the different kinds of control systems that are employed for GTIs along with their features were reviewed. It can again be observed that none of the controller can be considered the best since each controller is advantageous in its own way. From the studies it is found that the non-linear controllers performed much better than the other controller in all aspects but one has to compromise on the complexity factor since the non-linear controllers are the most complex in comparison to the other controllers. Hence we can conclude that each feature for a GTI inverter needs to select based on the requirements of the designer.

REFERENCES

[1]   Eltawil, M. A., & Zhao, Z. "Grid-connected photovoltaic power systems: Technical and potential problems-A review". *Renewable and sustainable energy reviews*, Vol. 14, No. 1, pp. 112-129, 2010.
[2]   Abdar, H. M., Chakraverty, A., Moore, D. H., Murray, J. M., & Loparo, K. A. "Design and implementation a specific grid-tie inverter for an agent-based microgrid". In *2012 IEEE Energytech, IEEE*, pp. 1-6, May 2012.
[3]   Yang, Y., & Blaabjerg, F. "Overview of single-phase grid-connected photovoltaic systems". *Electric Power Components and Systems*, Vol. 43 No. 12, pp. 1352-1363, 2015.
[4]   Hartono, B. S., & Setiabudy, R. "Review of microgrid technology". In *2013 international conference on QiR, IEEE*, pp. 127-132. June 2013.
[5]   Setiabudy, R., & Hartono, B. S. "Analysis Characteristics of On/Off Grid Tie Inverter and Implementation in Microgrid", *TELKOMNIKA (Telecommunication, Computing, Electronics and Control),* Vol. 11 No. 3, pp. 441-450, 2013.
[6]   Varia, D. "DC To AC Converter As Grid Tie Inverter & Smart Home Application" *Researchgate,* Vol. 5, No. 4, pp. 1-4, 2013.
[7]   Yang, B., Li, W., Gu, Y., Cui, W., & He, X. "Improved transformerless inverter with common-mode leakage current elimination for a photovoltaic grid-connected power system." *IEEE transactions on power electronics*, Vol. 27 No. 2, pp. 752-762, 2011.
[8]   Bin G, Dominic J, Jih-Sheng L, Chien-Liang C, LaBella T, Baifeng C. "High reliability and efficiency single-phase transformerless inverter for gridconnected photovoltaic systems". *IEEE Trans Power Electron*, Vol. 28 No. 5, pp. 2235-45, 2013.
[9]   Yu, W., Lai, J. S., Qian, H., Hutchens, C., Zhang, J., Lisi, G., ... & Hegarty, T. "High-efficiency inverter with H6-type configuration for photovoltaic non-isolated ac module applications". In *2010 Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), IEEE*, pp. 1056-1061, February 2010.
[10]   Ji, B., Wang, J., & Zhao, J. "High-efficiency single-phase transformerless PV H6 inverter with hybrid modulation method". *IEEE Transactions on Industrial Electronics*, Vol. 60 No. 5, pp. 2104-2115, 2012.
[11]   Wang, J., Ji, B., Zhao, J., & Yu, J. "From H4, H5 to H6-Standardization of full-bridge single phase photovoltaic inverter topologies without ground leakage current issue". In *2012 IEEE Energy Conversion Congress and Exposition (ECCE),* IEEE, pp. 2419-2425, September 2012.
[12]   Islam, M., Mekhilef, S., & Albatsh, F. M. "An improved transformerless grid connected photovoltaic inverter with common mode leakage current elimination," *7th IET International Conference on Power Electronics, Machines and Drives (PEMD 2014)*, 2014.
[13]   Xiao, H., Xie, S., Chen, Y., & Huang, R. "An optimized transformerless photovoltaic grid-connected inverter". *IEEE transactions on industrial electronics*, Vol. 58 No. 5, pp. 1887-1895, 2010.
[14]   Kerekes, T., Teodorescu, R., Rodríguez, P., Vázquez, G., & Aldabas, E. "A new high-efficiency single-phase transformerless PV inverter topology". *IEEE Transactions on industrial electronics*, Vol. 58 No. 1, pp. 184-191, 2011.
[15]   Zhang, L., Sun, K., Feng, L., Wu, H., & Xing, Y. "A family of neutral point clamped full-bridge topologies for transformerless photovoltaic grid-tied inverters." *IEEE Transactions on power electronics*, Vol. 28 No. 2, pp. 730-739, 2012.
[16]   Araújo, S. V., Zacharias, P., & Mallwitz, R. "Highly efficient single-phase transformerless inverters for grid-connected photovoltaic systems." *IEEE Transactions on Industrial Electronics*, Vol. 57 No. 9, pp. 3118-3128, 2010.

[17] Gu, Y., Li, W., Zhao, Y., Yang, B., Li, C., & He, X. "Transformerless inverter with virtual DC bus concept for cost-effective grid-connected PV power systems". *IEEE Transactions on Power Electronics*, Vol. 28 No. 20, pp. 793-805, 2012.

[18] Zhang, L., Sun, K., Feng, L., Wu, H., & Xing, Y. "A family of neutral point clamped full-bridge topologies for transformerless photovoltaic grid-tied inverters." *IEEE Transactions on Power Electronics*, Vol. 28 No. 2, pp. 730-739, 2013.

[19] Gu, B., Dominic, J., Lai, J. S., Chen, C. L., LaBella, T., & Chen, B. "High reliability and efficiency single-phase transformerless inverter for grid-connected photovoltaic systems." *IEEE Transactions on Power Electronics*, Vol. 28 No. 5, pp. 2235-2245, 2012.

[20] Miret, J., Camacho, A., Castilla, M., de Vicuña, L. G., & Matas, J. "Control scheme with voltage support capability for distributed generation inverters under voltage sags." *IEEE Transactions on Power Electronics*, Vol. 28 No. 11, pp. 5252-5262, 2013.

[21] Liu, Z., Liu, J., & Zhao, Y. "A unified control strategy for three-phase inverter in distributed generation." *IEEE Transactions on power electronics*, Vol. 29 No. 3, pp. 1176-1191, 2014.

[22] Busada, C., Jorge, S. G., Leon, A. E., & Solsona, J. "Phase-locked loop-less current controller for grid-connected photovoltaic systems." *IET Renewable Power Generation*, Vol. 6 No. 6, pp. 400-407, 2012.

[23] Castilla, M., Miret, J., Camacho, A., Matas, J., & de Vicuña, L. G. "Reduction of current harmonic distortion in three-phase grid-connected photovoltaic inverters via resonant current control." *IEEE transactions on industrial electronics*, Vol. 60 No. 4, pp. 1464-1472, 2013.

[24] Xu, J., Xie, S., & Tang, T. "Active damping-based control for grid-connected $ LCL $-filtered inverter with injected grid current feedback only." *IEEE Transactions on Industrial Electronics*, Vol. 61 No. 9, pp. 4746-4758, 2013.

[25] Chhabra, M., & Barnes, F. "Robust current controller design using mu-synthesis for grid-connected three phase inverter." In *2014 IEEE 40th Photovoltaic Specialist Conference (PVSC), IEEE*, pp. 1413-1418, June 2014.

[26] Hornik, T., & Zhong, Q. C. "A Current-Control Strategy for Voltage-Source Inverters in Microgrids Based on $ H^{\infty} $ and Repetitive Control." *IEEE Transactions on Power Electronics*, Vol. 26 No. 3, pp. 943-952, 2010.

[27] Yang, S., Lei, Q., Peng, F. Z., & Qian, Z. "A robust control scheme for grid-connected voltage-source inverters." *IEEE transactions on Industrial Electronics*, Vol. 58 No. 1, pp. 202-212, 2010.

[28] Espi, J. M., Castello, J., Garcia-Gil, R., Garcera, G., & Figueres, E. "An adaptive robust predictive current control for three-phase grid-connected inverters." *IEEE Transactions on Industrial Electronics*, Vol. 58 No. 8, pp. 3537-3546, 2010.

[29] Jorge, S. G., Busada, C. A., & Solsona, J. A. "Frequency-adaptive current controller for three-phase grid-connected converters." *IEEE Transactions on Industrial Electronics*, Vol. 60 No. 10, pp. 4169-4177, 2012.

[30] Do, T. D., Leu, V. Q., Choi, Y. S., Choi, H. H., & Jung, J. W. "An adaptive voltage control strategy of three-phase inverter for stand-alone distributed generation systems." *IEEE Transactions on industrial Electronics*, Vol. 60 No. 12, pp. 5660-5672, 2012.

[31] Lim, J. S., Park, C., Han, J., & Lee, Y. I. "Robust tracking control of a three-phase DC-AC inverter for UPS applications. *IEEE Transactions on Industrial Electronics*, Vol. 61 No. 8, pp. 4142-4151, 2013.

[32] Sun, X., Tian, Y., & Chen, Z. "Adaptive decoupled power control method for inverter connected DG." *IET Renewable Power Generation*, Vol. 8 No. 2, pp. pp. 171-182, 2013.

[33] Jung, J. W., Vu, N. T. T., Dang, D. Q., Do, T. D., Choi, Y. S., & Choi, H. H. "A three-phase inverter for a standalone distributed generation system: Adaptive voltage control design and stability analysis." *IEEE transactions on energy conversion*, Vol. 29 No. 1, pp. 46-56, 2013.

[34] De Almeida, P. M., Duarte, J. L., Ribeiro, P. F., & Barbosa, P. G. "Repetitive controller for improving grid-connected photovoltaic systems." *IET Power Electronics*, Vol. 7 No. 6, pp. 1466-1474, 2014.

[35] Kalaiselvi, K. "Development of power flow controller for grid connected renewable energy sources using lyapnouv function." In *2014 International Conference on Green Computing Communication and Electrical Engineering (ICGCCEE), IEEE*, pp. 1-7, March 2014.

[36] Trabelsi, M., Ghazi, K. A., Al-Emadi, N., & Ben-Brahim, L. "An original controller design for a grid connected PV system." *In IECON 2012-38th Annual Conference on IEEE Industrial Electronics Society, IEEE*, pp. 924-929, October 2012.

[37] Passino, K. M. "Intelligent control: An overview of techniques." Department of Electical Engineering, Ohio State University, 2015.

[38] Jamil, M., Arshad, R., Rashid, U., Ayaz, Y., & Khan, M. N. "Design and analysis of repetitive controllers for grid connected inverter considering plant bandwidth for interfacing renewable energy sources." In *2014 International Conference on Renewable Energy Research and Application (ICRERA), IEEE*, pp. 468-473, October 2014.

[39] Liu, T., & Wang, D. "Parallel structure fractional repetitive control for PWM inverters." *IEEE Transactions on Industrial Electronics*, Vol. 62 No. 8, pp. 5045-5054, 2015.

[40] Nazir, R., Zhou, K., Watson, N. R., & Wood, A. "Frequency adaptive repetitive control of grid-connected inverters." In *2014 International Conference on Control, Decision and Information Technologies (CoDIT), IEEE*, pp. 584-588, November 2014.

[41] Niroomand, M., & Karshenas, H. R. "Review and comparison of control methods for uninterruptible power supplies." In *2010 1st Power Electronic & Drive Systems & Technologies Conference (PEDSTC), IEEE*, pp. 18-23, February 2010.

[42] Konstantopoulos, G. C., Zhong, Q. C., & Ming, W. L. "PLL-less nonlinear current-limiting controller for single-phase grid-tied inverters: design, stability analysis, and operation under grid faults." *IEEE Transactions on Industrial Electronics*, Vol. 63 No. 9, pp. 5582-5591, 2016.

[43] Mohan, A., & Mathew, D. "High performance stand-alone and grid connected inverter using adaptive total sliding mode controller." In *2013 International Conference on Advanced Computing and Communication Systems, IEEE*, pp. 1-6, December 2013.

[44] Zhang, X., Chen, P., Yu, C., Li, F., Do, H. T., & Cao, R. "Study of a current control strategy based on multisampling for high-power grid-connected inverters with an LCL filter." *IEEE Transactions on Power Electronics*, Vol. 32 No. 7, pp. 5023-5034, 2016.

[45] Hao, X., Yang, X., Liu, T., Huang, L., & Chen, W. "A sliding-mode controller with multiresonant sliding surface for single-phase grid-connected VSI with an LCL filter." *IEEE Transactions on Power Electronics*, Vol. 28 No. 5, pp. 2259-2268, 2012.

[46] Kang, S. W., & Kim, K. H. "Sliding mode harmonic compensation strategy for power quality improvement of a grid-connected inverter under distorted grid condition." *IET Power Electronics*, Vol. 8 No. 8, pp. 1461-1472, 2015.

[47] Mahmud, M. A., Pota, H. R., & Hossain, M. J. "Nonlinear controller design for single-phase grid-connected photovoltaic systems using partial feedback linearization." In *2012 2nd Australian Control Conference, IEEE*, pp. 30-35, November 2012.

[48] Mahmud, M. A., Hossain, M. J., Pota, H. R., & Roy, N. K. "Robust nonlinear controller design for three-phase grid-connected photovoltaic systems under structured uncertainties." *IEEE transactions on power delivery*, Vol. 29 No. 3, pp. 1221-1230, 2014.

[49] Yao, Z., & Xiao, L. "Control of single-phase grid-connected inverters with nonlinear loads." *IEEE Transactions on Industrial Electronics*, Vol. 60 No. 4, pp. 1384-138, 2011.

[50] Li, Y., Hao, X., Yang, X., Xie, R., & Liu, T. "A variable-band hysteresis modulated multi-resonant sliding-mode controller for three-phase grid-connected VSI with an LCL-filter." In *2013 IEEE ECCE Asia Downunder, IEEE*, pp. 670-674, June 2013.

[51] Putri, A. I., Rizqiawan, A., Rozzi, F., Zakkia, N., Haroen, Y., & Dahono, P. A. "A hysteresis current controller for grid-connected inverter with reduced losses." In *2016 2nd International Conference of Industrial, Mechanical, Electrical, and Chemical Engineering (ICIMECE), IEEE*, pp. 167-170, October 2016.

[52] Jena S, Babu BC. "Power quality improvement of 1-Φ grid-connected PWM inverter using fuzzy with hysteresis current controller." In *10th International Conference on Environment And Electrical Engineering*, pp. 1-4, 2011.

[53] Ichikawa R, Funato H. "Single phase utility interface inverter based on digital hysteresis current controller-Operational characteristics both grid-connected mode and islanding mode." In *15th International Power Electronics and Motion Control Conference*, pp. LS8b.3-1-LS8b.3-8, 2012.

[54] Hao, X., Yang, X., Xie, R., Huang, L., Liu, T., & Li, Y. "A fixed switching frequency integral resonant sliding mode controller for three-phase grid-connected photovoltaic inverter with LCL-filter." In *2013 IEEE ECCE Asia Downunder, IEEE,* pp. 793-798, June 2013.

[55] Vieira, R. P., Stefanello, M., Tambara, R. V., & Gründling, H. A. "Sliding mode control in a multi-loop framework for current control of a grid-tied inverter via LCL-filter." In *IECON 2014-40th Annual Conference of the IEEE Industrial Electronics Society, IEEE* pp. 4384-4389, October 2014.

[56] Lin, F. J., Lu, K. C., & Ke, T. H. "Probabilistic Wavelet Fuzzy Neural Network based reactive power control for grid-connected three-phase PV system during grid faults." *Renewable energy*, Vol. 92, 437-449, 2016.

[57] Zhao, Q., Ye, Y., Xu, G., & Zhu, M. "Improved repetitive control scheme for grid-connected inverter with frequency adaptation." *IET Power Electronics*, Vol. 9 No. 5, pp. 883-890, 2016.

[58] Zhang, X., Chen, P., Yu, C., Li, F., Do, H. T., & Cao, R. "Study of a current control strategy based on multisampling for high-power grid-connected inverters with an LCL filter." *IEEE Transactions on Power Electronics*, Vol. 32 No. 7, pp. 5023-5034, 2016.

BIOGRAPHIES OF AUTHOR

Salam Ibrahim Khather received a B.Sc. degree in Electrical Engineering from Mosul University in 2005. In 2008, he achieved his M.Sc. in Electrical Engineering from Mosul University. He started his career working as an Electrical Engineer in the Power Plant and Electrical Substations (2009-2017). Then, he started his academic journey working as an assistant lecturer at Ninevah University. His major research areas are Power and Machines, Control Systems and Power Electronics Applications.