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Simulation Implementation of ANFIS Control For Renewable Interfacing Inverter with Capacitors in 3P4W Distribution Network

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Abstract:

Power electronics plays an important role in controlling the grid-connected renewable energy sources. This paper presents a novel adaptive neuro-fuzzy control approach for the renewable interfacing inverter. The main objective is to achieve smooth bidirectional power flow and nonlinear unbalanced load compensation simultaneously, where the conventional proportional-integral controller may fail due to the rapid change in the dynamics of the highly nonlinear system. The combined capability of neuro-fuzzy controller in handling the uncertainties and learning from the processes is proved to be advantageous while controlling the inverter under fluctuating operating conditions.

The inverter is actively controlled to compensate the harmonics, reactive power, and the current imbalance of a three-phase four-wire (3P4W) nonlinear load with generated renewable power injection into the grid simultaneously. This enables the grid to always supply/absorb a balanced set of fundamental currents at unity power factor even in the presence of the 3P4W nonlinear unbalanced load at the point of common coupling. In electric power distribution, capacitors are used for power factor correction. Such capacitors often come as three capacitors connected as a three phaseload. Usually, the values of these capacitors are given not in farads but rather as a reactive power in volt-amperes reactive (VAr).

The purpose is to counteract inductive loading from devices like electric motors and transmission lines to make the load appear to be mostly resistive. In high-voltage direct current transmission systems, power factor correction capacitors may have tuning inductors to suppress harmonic currents that would otherwise be injected into the AC power system. The proposed system is developed and simulated in MATLAB/ Sim Power System environment under different operating conditions. The digital signal processing and control engineering-based laboratory experimental results are also provided to validate the proposed control approach.

Introduction:

The increase in global energy demand, air pollution, global warming, and the rapid evaporation of fossil fuel has made it necessary to look toward renewable sources as a future energy solution. However, the higher penetration level of these intermittent renewable energy sources (RESs) poses a great threat to network security. Therefore, the RESs are required to comply with strict technical and regulatory frameworks to ensure the safe, reliable, and efficient operation of the overall network .With the advancement in power electronics and digital control technology, the RES can now be actively controlled to enhance the system stability with an improved power quality at the point of common coupling (PCC).Recently, a lot of control strategies for renewable interfacing inverter have been introduced. Some control strategies for grid-connected inverters incorporating power quality solution have also been investigated by researchers. In an application an inverter operates as an active inductor at a certain frequency to absorb the harmonic current. However, the exact calculation of network inductance in real time is very difficult and may deteriorate the control performance.

A similar approach in which a shunt active filter acts as an active conductance to damp out the harmonics in distribution network is proposed in one project. In one application , a control strategy for renewable interfacing inverter based on p–q theory is proposed. A similar decoupled current control technique using PI regulator in d–q reference frame is presented in a circuit. In both of these strategies, the load and inverter current sensing is required to compensate the load current harmonics.The current-regulated voltage source inverters have a very wide range of applications such as the grid synchronization of RES, static reactive power compensation, uninterruptible power supply, active power filters (APF), and adjustable speed drives. However, in the case of the very first application, the installed inverter rating has a very low utilization factor due to the intermittent nature of RES.

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According to a project, the expected RES output during peak is nearly 60% of the rated output, yet the annual capacity factor may be in the 20%–30% range.Therefore, the authors have incorporated the APF features in the RES interfacing inverter to maximize its utilization without any additional hardware cost. Moreover, the proposed control strategy requires only the grid current sensing, which further reduces the cost and complexity. The grid-interfacing inverter injects the generated active power from renewable as well as compensates the load reactive power, current harmonics, and load imbalance in a three-phase four-wire (3P4W) system. This enables the grid to always supply a balanced set of sinusoidal currents at unity power factor (UPF).Since the inverter works under highly fluctuating operating conditions, it is not possible to set the optimal value of gains for the conventional PI regulator in an application. This may lead to a false operation of the inverter. To alleviate this problem, an adaptive neuro-fuzzy controller is developed, which has well-known advantages in modeling and control of a highly nonlinear system. An adaptive error back propagation method is used to update the weights of the system for the fast convergence of control.

System Configuration And Control:

The system under consideration with control description is shown in Fig. 1, where a RES is connected on the dc link of a grid-interfacing four-leg inverter. The fourth leg of the inverter is utilized to compensate the neutral current of 3P4W network. Here, the inverter is a key element since it delivers the power from renewable to grid and also solves the power quality problem arising due to unbalanced nonlinear load at PCC. The duty ratio of inverter switches are varied in a power cycle such that the combination of load and inverter-injected power appears as balanced resistive load to the grid, resulting into the UPF grid operation.The renewable source may be a dc source or an ac source with rectifier coupled to a dc link. The regulation of dc-link voltage carries the information regarding the exchange of active power in between renewable source and grid. The error between reference dc-link voltage (V*dc) and actual dc-link voltage (Vdc) is given to the neuro-fuzzy controller, and the same error is used to update the weights. The output of neuro-fuzzy controller is further modified by subtracting the renewable injected current (iRen). This results into the reference d-axis current (i*d), while the reference q-axis current (i*q) is set to zero for UPF grid operation.

The grid-synchronizing angle (θ) obtained from phase lock loop is used to generate the reference grid currents (i*a, i*b, and i*c). The reference grid neutral current i*n is set to zero to achieve balanced grid-current operation. The hysteresis current controller is utilized to force the actual grid currents to track the reference grid currents accurately. This enables the grid to supply/absorb only the fundamental active power, while the RES-interfacing inverter fulfills the unbalance, reactive, and nonlinear current requirements of 3P4W load at PCC.

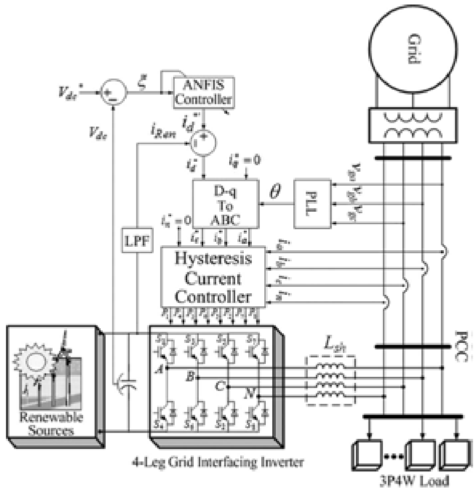

Fig.1.Schematic and control description of proposed renewable-based distributed generation system.

Design of adaptive neuro-fuzzy controller:

An optimized adaptive-network-based fuzzy inference system(ANFIS) having a 1:3:3:3:1 architecture is generated fromthe initial data using MATLAB/anfiseditoras shown in Fig. 2.This Takagi-Sugeno-Kang fuzzy model-based ANFIS architecturehas one input and one output, which is further tunedonline using the error back propagation method as shown inFig. 3. The error between reference dc-link voltage and actualdc-link voltage (ξ = V*dc – Vdc) is given to the neuro-fuzzycontroller, and the same error is used to tune the preconditionand consequent parameters.

The control of dc-link voltage givesthe active power current component (i*d), which is furthermodified to take into account the active current componentinjected from RES (iRen). The node functions of each layer inthe ANFIS architecture are described as follows:Layer 1: This layer is also known as the fuzzification layer where each node is represented by a square. Here, three

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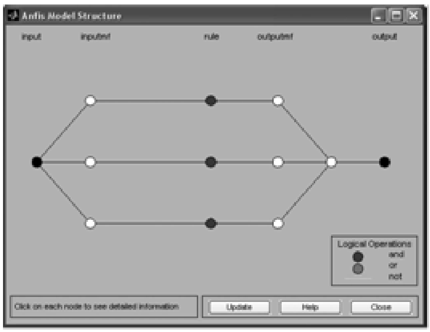

Fig.2:Optimized ANFIS architecture suggested by MATLAB/an-fis editor

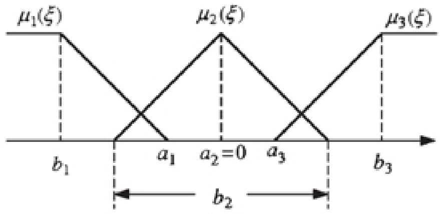

Fig.3. Fuzzy membership functions.

Member ship functions are assigned to each input. The trapezoidal and triangular membership functions are used to reduce the computation burden as shown in Fig. 4, and their corresponding node equations are given as follows: where the value of the parameters {ai, bi} changes with the change in error and accordingly generates the linguistic value of each membership function. Parameters in this layer are referred as premise parameters or precondition parameters.

Layer 2: Every node in this layer is a circle labeled as Π which multiplies the incoming signals and forwards it to the next layer

μi= μAi(ξ1) • μBi(ξ2) • • •, i= 1, 2, 3. (4)

However, in our case, there is only one input, so this layer can be ignored and the output of the first layer will directly pass to the third layer. Here, the output of each node represents the firing strength of a rule.

Layer 3: Every node in this layer is represented by a circle. This layer calculates the normalized firing strength of each rule as given in the following:

μi= μiμ1 + μ2 + μ3, i= 1, 2, 3. (5)

Layer 4: Every node in this layer is a square node with a node function

Oi= μi• fi = μi_ai0 + ai1• ξ_, i= 1, 2, 3 (6)

Where the parameters {ai0, ai1}are tuned as the function ofthe input (ξ). The parameters in this layer are also referred as consequent parameters.

Layer 5: This layer is also called the output layer which computes the output as given in the following:

Y = μ1• f1 + μ2• f2 + μ3• f3. (7)

The output from this layer is multiplied with the normalizing factor to obtain the active power current component (i*d).

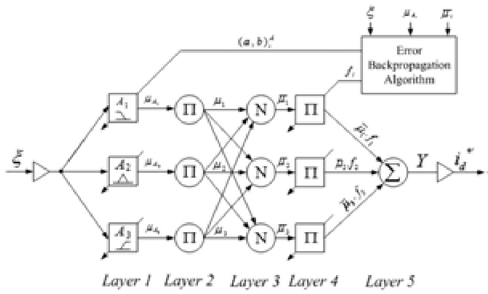

Fig. 4: Schematic of the proposed ANFIS-based control architecture.

SIMULATIONRESULTS:

An extensive simulation study has been carried out for the renewable interfacing inverter in order to verify the proposed control strategy. The system under consideration is simulated using the Sim Power System tool box of MATLAB/Simu link. An IGBT-based four-leg current-controlled voltage source inverter is actively controlled to achieve the balanced sinusoidal grid currents at UPF despite the highly unbalanced nonlinear load at the PCC under varying renewable generating conditions. A RES with variable output power is connected on the dc link of the grid-interfacing inverter. An unbalanced 3P4W nonlinear variable load, whose harmonics, unbalance, and reactive power are to be compensated, is connected on the PCC. The waveforms of grid voltage (Vg), grid current (ig), unbalanced load current (il), injected inverter currents (iinv), and dc-link voltage (Vdc) are shown in Fig. 5. In Fig. 6, the traces of phase a grid current (iga), phase a load current (ila), and phase a inverter current (iinva) are shown w.r.t. phase a grid voltage (Vga). In addition, the waveforms of grid neutral current (ign), load neutral current (iln), and inverter neutral current (iinvn) are also shown in the same diagram. Fig. 7 shows the traces of phase a grid voltage (Vga) and phase a grid current (iga) on the same plot, phase a load current (ila), and phase a inverter current (iinva). The main purpose of the proposed control strategy is to inject the generated renewable active power, load harmonics, and reactive power in such a way that only the injection/absorption of the active power takes place in the grid. Initially, the generated active power is more than the load active power demand, so the extra

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generated power is being injected into the grid. This fact can be verified from the traces of different currents, where the current supplied from the renewable is more than the load current, so the difference of these is being injected into the grid as evident from the out-of-phase relation of the grid voltage (Vga) and grid current (iga). In addition, the inverter is also supplying the harmonics, neutral current, and reactive current component of the load current demand. This results into the perfectly balanced sinusoidal grid current even in the presence of a 3P4W unbalanced nonlinear load at PCC as shown in Fig. 5. This fact can also be visualized from Figs. 6 and 7, where the phase a grid current (iga) is purely sinusoidal and in phase opposition with the phase a grid voltage (Vga).Fig. 7.1: Simulation results. (a) Grid voltages. (b) Grid currents. (c) Unbalanced load currents. (d) Inverter currents.Here, it can also be noticed that the load neutral current (iln) is fully supplied by the inverter neutral current (iinvn). This results into the zero value of the grid neutral current (in). At t = 0.375 s, there is a sudden increase in the load power demand, and the generated renewable active power is not sufficient enough to meet this enhanced demand.

At this instant, the renewable interfacing inverter supplies the generated active power and total load reactive power demand, while the grid supplies only the deficient amount of load active power. This fact can be verified from Figs. 6 and 7, where the phase a grid Fig. 5. Simulation results. (a) Grid voltages. (b) Grid currents. (c) Unbalanced load currents. (d) Inverter currents. current, which was in the opposite phase to the grid voltage before t = 0.375 s, is now in phase with the grid voltage and the load neutral current is still being supplied from the inverter. Thus, from the simulation results, it is clear that the grid always works at UPF under fluctuating renewable power generation and dynamic load conditions with an unbalanced nonlinear load at PCC. It can also be noticed that the dc-link voltage is almost constant at 300 V under both steady state and dynamic conditions, except negligible deviation due to a change in injected active power. Here, the dc-link voltage is shown on a very small scale, just to demonstrate the performance of the proposed ANFIS controller in controlling the dc-link voltage.

EXPERIMENTAL RESULTS:

The proposed adaptive neuro-fuzzy controller is implemented in real time on a four-leg IGBT-based inverter Fig. 6. Simulation results: Phase grid voltage, grid current, load current, inverter current, load neutral current, and inverter neutral current. Fig. 7.Simulation results. (a) Phase a grid voltage and current. (b) Load current. (c) Inverter current. ing digital signal processing and control engineering DS1104, Where as the RES is emulated with an auxiliary inverter connected on a dc link. It takes a sampling time of 75 µs to realize the proposed ANFIS controller in real time. The 3P4W nonlinear load is composed of three-phase nonlinear RL load, one-phase RL nonlinear load connected in between phase a and neutral, and a single-phase RL load in between phase b and neutral.An extensive experimental study is carried out to highlight the performance of the inverter as a multi objective device.

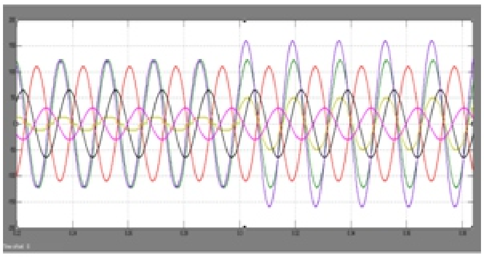

Fig.5: Simulation results: Phase a grid voltage, grid current, load current,inverter current, load neutral current, and inverter neutral current.

The inverter operation is mainly divided into two parts: active filter operation and renewable interfacing operation. All the experimental results are captured with an oscilloscope in real time as shown in Figs. 8–10.

ACTIVE FILTER OPERATION:

Filtering capabilities of the inverter are demonstrated. In Fig. 8(a), the traces of 3P4W grid currents are shown before and after compensation. Initially, the grid supplies an unbalanced nonlinear load current with a high neutral current, which is highly undesirable.

In order to compensate this unbalanced nonlinear current, the inverter currents are injected in such a way that the combination of load and inverter current appears as a balanced set of fundamental currents. The traces of the injected inverter currents are shown in Fig. 8(b), just before and after compensation.

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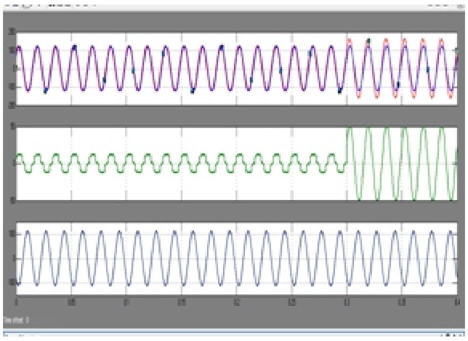

Fig.6: Simulation results. (a) Phase a grid voltage and current. (b) Loadcurrent. (c) Inverter current.

Here, it can be easily noticed that the grid currents are perfectly balanced with a sinusoidal profile. Moreover, the inverter is Fig. 8. Experimental results: (a) Grid currents and (b) inverter currents, just before and after compensation. Success fully able to supply the load neutral current demand locally, as evident from the zero value of the grid neutral current (ign).

RENEWABLE INTERFACING OPERATION:

In this mode of operation, the bidirectional power flow capabilities of the renewable interfacing inverter are discussed.Here, the main objective is not only the grid interfacing of the renewable but also to compensate the 3P4W nonlinear unbalanced load at PCC simultaneously. The inverter supplies the renewable injected current and the nonlinear unbalanced component of load current. This enables the grid to always supply/absorb only the balanced set of currents at UPF. In Fig. 9, the traces of grid voltage (Vg), grid current (ig), load current (il), and inverter injected current (iinv) are shown. In Fig. 9(a), initially, the inverter current is supporting the load current partially and it goes on increasing. At middle stage, the inverter current is almost equal to the load current, and this forces the grid current to be almost zero. In the last stage, the inverter current is more than the load demand, and at this stage, the grid absorbs this excessive amount of current as evident by the out-of-phase relationship of the grid voltage and current. Similarly, in Fig. 9(b), the grid current is again shown from Fig. 9. Experimental results: Inverter performance under the renewable interfacing mode of operation.Fig. 10. Experimental results: Inverter performance under the renewable interfacing mode of operation. absorption mode to supplying mode with the corresponding change in the inverter current.

Fig. 10 shows the traces of grid voltage (Vg) and grid current (ig) on the same axis, dclink voltage (Vdc), and inverter injected current (iinv), where it can benoticed that the dc-link voltage is almost constant irrespective of any kind of variation in injected inverter current. A comparative table showing the total harmonic distortions (THDs) and unbalancefactor (UF) before and after compensation is given in Table I, where the percentage UF is calculated separately for each phase using %UFabc= |iabc− iavg.|iavg.• 100. (8)

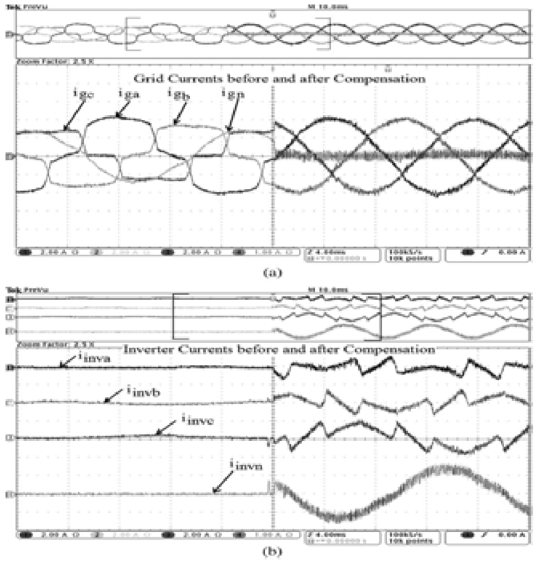

Fig.7: Experimental results: (a) Gridcurrents and (b) inverter currents, justbefore and after compensation.

In this mode of operation, only the active Here, it can be noticed that the grid current is highly unbalanced with the UFs of 20.48%, 0.41%, and 21.07% in phase a, phase b, and phase c, respectively, resulting into the flow of a 1.1-Acurrent in neutral wire. The percent THDs present in phase a, phase b, and phase c currents are 14.7%, 18.2%, and 23.2%, respectively.

However, once after the interconnection of the renewableinterfacing inverter, the grid currents become almost balanced and harmonic free with a very low UF of 0.7%, a very low level of THDs of 2.9%, and an almost zero current in gridsideinterfacing mode of operation.neutral wire.

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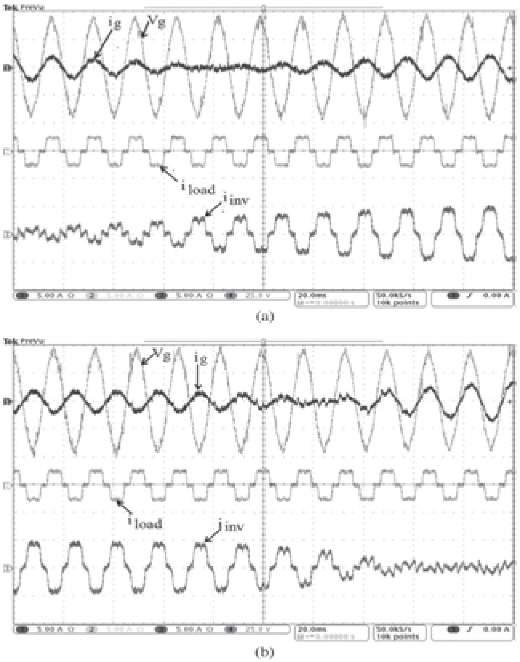

Fig.8: Experimental results: Inverter performance under the renewable interfacing mode of operation.

SYSTEM CONFIGURATION AND CONTROL:

The system under consideration with control description is shown in Fig. 1, where a RES is connected on the dc link of a grid-interfacing four-leg inverter. The fourth leg of the inverter is utilized to compensate the neutral current of 3P4W network. Here, the inverter is a key element since it delivers the power from renewable to grid and also solves the power quality problem arising due to unbalanced nonlinear load at PCC. The duty ratio of inverter switches are varied in a power cycle such that the combination of load and inverter-injected power appears as balanced resistive load to the grid, resulting into the UPF grid operation.

Power Factor Correction Capacitors:

Power factor correction capacitors and harmonic filters are an essential part of modern electric power systems. Power factor correction capacitors are the simplest and most economical means of increasing the capacity of any power system, minimizing energy losses and correcting load power factor. In addition, power factor penalties can be reduced and power quality can be greatly enhanced. There are several reasons to correct poor power factor. The first is to reduce or eliminate a power factor penalty charged by the utility. Another reason is that your existing transformer is, or shortly will be, at full capacity and installing power factor correction capacitors can be a very cost-effective solution to installing a brand new service. Depending on theamount of power factor correction (kVAR that needs to be injected into the electrical system to improve the power factor) and the dynamic nature of the load, a fixed or switched capacitor bank may be the best solution. When capacity becomes a problem, the choice of a solution will be dependent upon the size of the increase needed. Like all power quality solutions,there are many factors that need to be considered when determining which solution will be best to solve your power factor problem.

Harmonic Filtering:

As the world becomes more dependent on electric and electronic equipment, the likelihood that the negative impact of harmonic distortion increases dramatically. The efficiency and productivity gains from these increasingly sophisticated pieces of equipment have a negative side effect…increased harmonic distortion in the power lines. The difficult thing about harmonic distortion is determining the cause. Once this has been determined, the solution can be easy.Passive and active harmonic filtering equipment will mitigate specific harmonic issues, and correct poor power factor as well.

EXTENSION TO THE EXISTING APPLICATION:

In electric power distribution, capacitors are used for power factor correction. Such capacitors often come as three capacitors connected as a three phaseload. Usually, the values of these capacitors are given not in farads but rather as a reactive power in volt-amperes reactive (VAr). The purpose is to counteract inductive loading from devices like electric motors and transmission lines to make the load appear to be mostly resistive. Individual motor or lamp loads may have capacitors for power factor correction, or larger sets of capacitors (usually with automatic switching devices) may be installed at a load center within a building or in a large utility substation. In high-voltage direct current transmission systems, power factor correction capacitors may have tuning inductors to suppress harmonic currents that would otherwise be injected into the AC power system.

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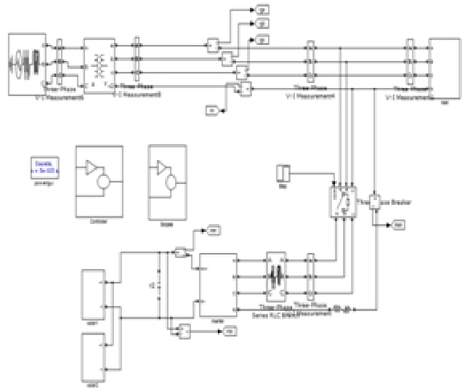

Fig.9: Simulation Circuit

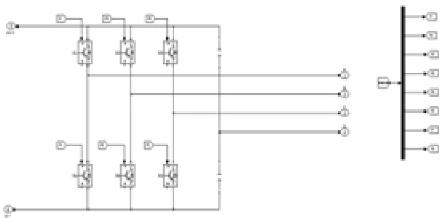

Fig.10: 4-leg inverter in which one leg is replaced with capacitor.

INVERTER PERFORMANCE AS A COMPENSATING DEVICE:

It can be noticed that the dc-link voltage is almost constant irrespective of any kind of variation in injected inverter current. A comparative table showing the total harmonic distortions (THDs) and unbalance factor (UF) before and after compensation is given in Table I, where the percentage UF is calculated separately for each phase using
%UFabc= |iabc− iavg.|iavg.• 100. (8)

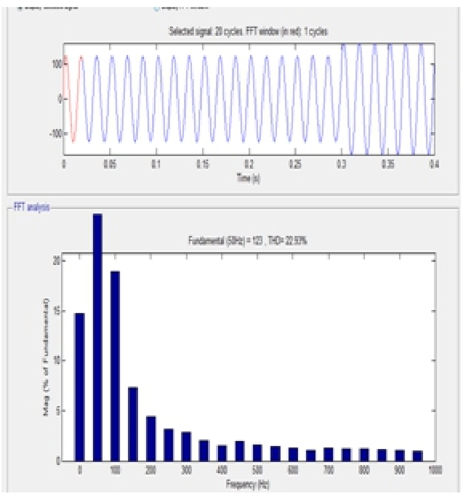

Fig.11: THD value for the 4-leg inverter with IGBT

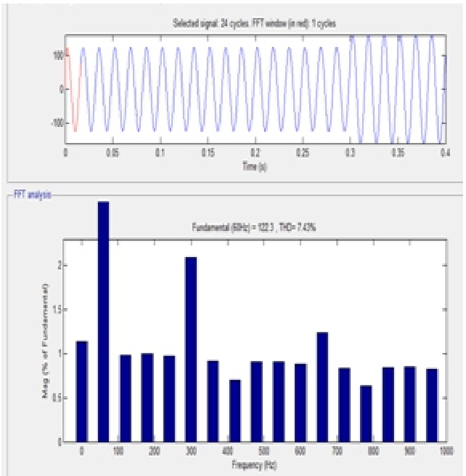

Fig.12: THD value for the 4-leg inverter with IGBT in which one leg is replaced with capacitors.

Here, it can be noticed that the grid current is highly unbalanced with the UFs of 20.48%, 0.41%, and 21.07% in phase a, phase b, and phase c, respectively, resulting into the flow of a 1.1-A current in neutral wire. The percent THDs present in phase a, phase b, and phase c currents are 14.7%, 18.2%, and 23.2%, respectively. However, once after the interconnection of the renewable interfacing inverter, the grid currents become almost balanced and harmonic free with a very low UF of 0.7%, a very low level of THDs of 2.9%, and an almost zero current in gridside neutral wire.

CONCLUSION:

This project has presented a novel adaptive neuro-fuzzy control algorithm for the renewable interfacing inverter. The controller works satisfactorily under the dynamic operating conditions. It has also been shown that the inverter is able to perform all the duties of the shunt APF while maintaining the smooth bidirectional power flow simultaneously. The simulation results supported by the experimental results are provided to validate the fact that the renewable interfacing inverter can act as a multi operation device in order to utilize its maximum rating. Power factor correction capacitors are the simplest and most economical means of increasing the capacity of any power system, minimizing energy losses and correcting load power factor. In addition, power factor penalties can be reduced and power quality can be greatly enhanced. The current unbalance, current harmonics, and load reactive power demand of an unbalanced nonlinear load at

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PCC are compensated effectively such that the grid side currents are always maintained as a balanced set (0% UF) of sinusoidal current (2.7% THD) at UPF. Moreover, the load neutral current is restricted to flow toward the grid side (almost zero) by supporting it locally from the fourth leg of the inverter which is replaced with capacitors.When the power generated from the renewable is more than the total load power demand, the grid-interfacing inverter with the proposed control approach successfully fulfills the total load demand (active, reactive, and harmonics) and delivers the remaining active power to the main grid at UPF operation.

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