EnhancingPowerQualityinSolar-PoweredEV Charging Stations Connected to aThree-Phase Grid

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Abstract: *The integration of photovoltaic (PV) systems into electric vehicle (EV) charging stations offers an ecofriendly alternative to conventional energy sources. However, it introduces significant power quality challenges due to the intermittentnatureofsolarenergy.ThispaperproposesahybridcontroltechniquecombiningRadialBasisFunctionNeural Network (ANN) and Proportional-Integral (PI) control to enhance power quality in PV based EV charging stations connected to a three-phase grid. The ANN dynamically adjusts the PI controller gains in real-time, ensuring optimal performance under varying operational conditions. Simulation results under different scenarios, including normal operation and fault conditions, demonstrate the superior performance of the proposed method in maintaining voltage stability and reducing harmonic distortion compared to traditional control techniques. This study contributes to the field by offering a robustsolutionforimprovingpowerqualityingrid-connectedPVsystems,facilitatingthereliableintegrationofrenewable energy sources into the grid.*

Keywords—EVchargingstation,DC-DCbidirectionalconverter,powerquality,solarphotovoltaic,VSC.

I. INTRODUCTION

For the last two decades renewable energy is very well known. Renewable energy sources are forecasted to turn out to be competitive with conventional power generation systems.The environmental concernsfor increased pollution, resource conservation have led to the increase in the usage of the electrical vehicles (EVs). PV-based EV charging stations utilize solar panels to generate electricity, which is then used to charge electric vehicles.These stations can operate in standalone modeorbeconnectedtothegrid.Grid-connectedPVsystemsarepreferredduetotheirabilitytofeedexcesspowerbackto the grid and draw power during low solar generation periods. However, the integration of these systems with the grid introduces power quality challenges that must be addressed to ensure stable operation.

Most of thetimes EVisparked with a largeamount of energy storedin it.WhenEVisidle, the power stored in the battery is supplied to the grid to meet the peak power requirement.To accomplish this objective, the EVcharger needs to support thebi-directionalactivepowerflow.WhenEVsuppliespowertothegrid,theprocedureisnamedasvehicletogrid(V2G). In this mode, the EVchargesmay also provide the reactive power support to the grid. Power quality refers to the stability, reliability, and efficiency of electrical power supply. In gridconnected systems, poor power quality can lead to equipment malfunction,energylosses,andreducedlifespanofelectricalcomponents.ForPV-basedEVchargingstations,maintaining high power quality is essential to ensure efficient energy transfer, protect infrastructure, and comply with regulatory standards.

Several control strategies have been proposed to enhance power quality in PV systems, including PI control, fuzzy logic control, and neural network-based approaches. Traditional PI controllers are widely used due to their simplicity and effectiveness in steady-state conditions. However, they may struggle with dynamic and nonlinear characteristics of PV systems. Advanced control techniques, such as neural networks and adaptive control, offer improved performance by dynamically adjusting control parameters based on real-time data.This charging station supports the bi-directional flowof power. The EV is connected at the DC-link of the charging station using a bidirectional converter. The benefit of a bidirectional converter is that it blocks the second harmonic current and the DC-link ripples to enter the EV battery and deterioratesthebatterybydecreasingitslifetime.Moreover,thedependencyoftheselectionoftheEVbatteryratingonthe DC-linkvoltageiseliminated.Thedutycycleofthebidirectionalconverteriscontrolledtocharge/dischargeofthebattery.

The PV array is used here for EV battery charging and the extra power is supplied to the utility to reduce the generation requirement. The VSC is utilized for the reactive power compensation demanded by the grid. The PV based EV charging stationimprovesthegridpowerqualityinthegridconnectedmodeandduringthegridfailure,itoperatesinthestandalone modeandPVarraygenerationisusedforthechargingtheEVbattery.Thesystemisalsotestedduringvariousdynamic conditions such as PV insolation variations, unbalancing of the grid voltages, compensation of the grid reactive power. Whenever, the grid is restored back, the charging station synchronizes to the grid.

Thecontrolofthechargingstationisdesignedusingthereferenceactivepowerandreactivepowercommand.Thereference active power command is decided by the EV owner whether to charge/ discharge the EV battery. The reference reactive power is selected according to the inductive/capacitive reactive power requirement for the persistent operation of the chargingstation.ThechargingstationiscontrolledinsuchamannerthatEVownerdecidesthecharging/dischargingofEV battery.IfitisrequiredtochargetheEVbatteryusinggridpower,thesystemoperationisknownasG2V(GridtoVehicle). However, if EVbattery discharges to provide power to the grid, the system operation is known asV2G (Vehicle to Grid). Moreover, the charging station has the ability to provide the reactive power compensation (lagging/leading) as per the requirement.

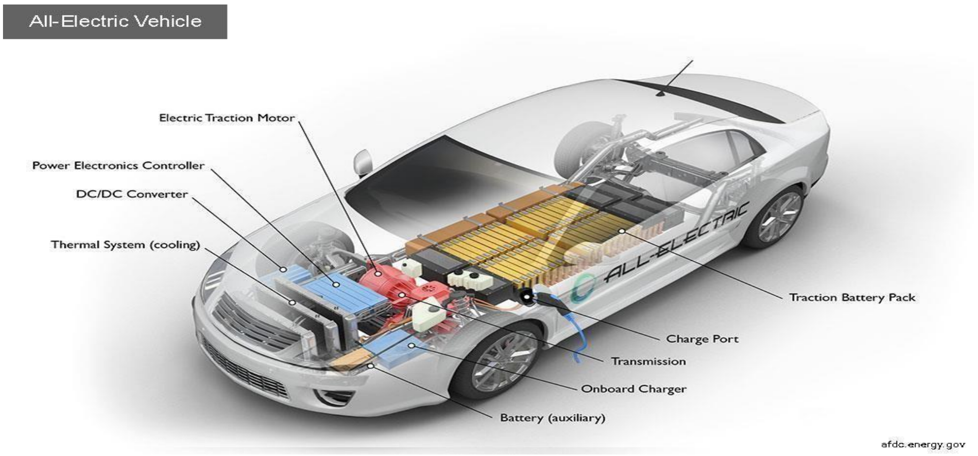


Fig.1OutlineofanElectricVehicle

II. SYSTEMCONFIGURATION

The fundamental block diagram of the single-stage P-V based EV charging station is illustrated in Fig. 2. The primary objective of this chargingstation isto utilize the DC power produced bythe PVarray to charge the EV battery.Abidirectional converter facilitates both the charging and discharging processes of the EVbattery.The PV array is directly connected to the DC-link, thereby eliminating the need for a boost converter and reducing theoverallcostofthechargingstation.AnIGBT-basedVoltageSourceConverter(VSC)isemployedtoconvert DC power toAC power for interfacing with the grid.The switches that connect the charging station to the grid are also based on IGBT technology.

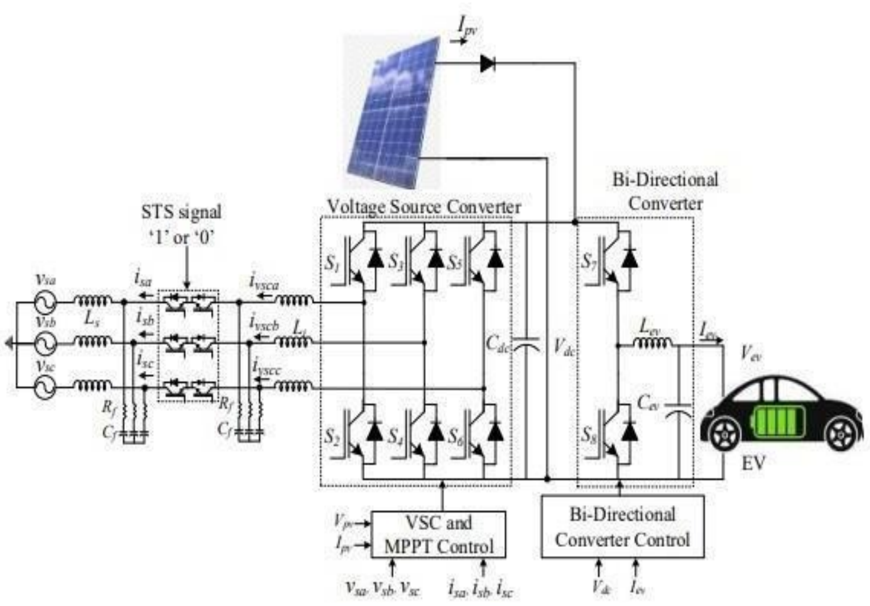


Fig.2Three-phaseThree-wiresingle-stagegrid-connectedPVsystemwithEV

A. ActivePowerReferenceCommand

This The active power reference command is determined based on the charging or discharging needs of the EV battery.ThiscommandissetbytheEVowner,whocanchoosetoeitherchargethebatteryordischargeittosupply power to thegrid.By discharging the battery andprovidingpower to thegridduring peakdemand,the EVowner canearnincentivesbysellingthispower.Itregulatesthemagnitudeandtypeofreactivepower,whetherinductive orcapacitive.ThecontrolmechanismoftheEVchargingstationiscategorizedintotwosections:VSCcontroland EVcharging/dischargingcontrol,whicharefurtherdividedintogrid-connectedmodecontrolandstandalonemode control.ControloftheEVchargingstationisclassifiedintotwosubsections –VSCandEVcharging/discharging control in grid connected mode control and standalone mode control.

Theactivepowerreferencecommandandthereactivepowerreferencecommandplayacrucialroleingeneratingthe VSC switching pulses during grid-connected operation.The charging and discharging of the EVbattery are managed through a DC-DC bidirectional converter. The detailed control scheme is outlined in the subsequent section.

B. VSCControlinGrid-ConnectedMode

1) The generation of VSC gate pulses in grid-connected mode is illustrated in Fig. 2. The active power reference command (Pref) influences the active component of the current (Ip), while the reactive power reference command (Qref) affectsthereactivecomponentofthecurrent(Iq).Theper-phaseactivecurrents(ipa,ipb,ipc)aredeterminedbymultiplying theactivecurrentcomponent(Ip)withthein-phaseunittemplates(upa,upb,upc).Likewise,theperphasereactivecurrents (iqa,iqb,iqc)arederivedbymultiplyingthereactivecurrentcomponent(Iq)withthequadrature-phaseunittemplates(uqa, uqb, uqc). Further details of the control mechanism are explained in the following sections

2) Whenthegridvoltagesareunbalanced,theirPSCsareestimatedasshowninFig.3.Theterminalvoltageamplitude is estimated from the PSCs as follows,

$$V_t = \sqrt{\frac{2}{3} \times (v_{pa}^2 + v_{pb}^2 + v_{pc}^2)}$$

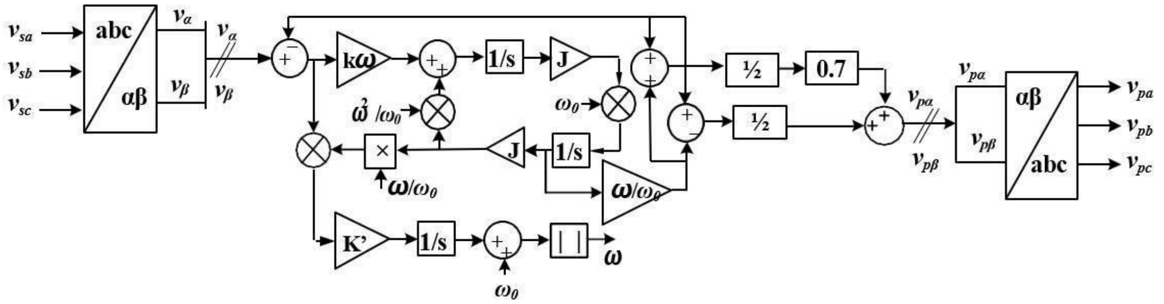


Fig.3Positivesequencegridvoltagesestimation

Estimating positive sequence grid voltages is crucial for monitoring and controlling power systems. Positive sequence componentsrepresentthebalancedpartofathree-phasesystem,whichisvitalfortheproperoperationofvariouselectrical equipment. Here’s a brief outline of the process:

1. **MeasurementCollection**:Gatherreal-timemeasurementsofthethree-phasevoltagesfromthepowergrid.These measurements are typically obtained from voltage transformers or other sensors installed in the system.

2. **PhaseVoltage Calculation**:

   - Representthethree-phasevoltagesVaV_aVa,VbV_bVb,andVcV_cVcasphasorsorcomplexnumbers. This can be done using:

$$V_a = |V_a|e^{j\theta_a}, \quad V_b = |V_b|e^{j\theta_b}, \quad V_c = |V_c|e^{j\theta_c}$$

where |Vx||V_x||Vx|isthemagnitudeandθxisthephaseangleofthe voltage.

3. **ClarkeTransformation**:
    - ApplytheClarke(orαβ0)transformationtoconvertthethree-phasevoltagesintotheαβ0components:

$$\begin{pmatrix} V_\alpha \\ V_\beta \\ V_0 \end{pmatrix} = \frac{2}{3} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix} \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix}$$

4. **PositiveSequenceCalculation**:
    - Calculatethepositivesequencecomponentusingthesymmetricalcomponentmethod. The positive sequence voltage V1 is given by:

$$V_1 = \frac{1}{3}(V_a + aV_b + a^2V_c)$$

wherea=ej^2π/3isaunitphasoroperator.

5. **InverseTransformation**:
    - Ifneeded,convertthepositivesequencevoltagebacktotheoriginalphasecoordinatesoruseitdirectly for analysis and control purposes.

6. **FilteringandValidation**:
    - Apply filtering techniques to the estimated positive sequence voltage to reduce noise and improve accuracy.
    - Validate the estimated positive sequence voltage against known standards or benchmarks to ensure reliability.

By following these steps, you can estimate the positive sequence grid voltages, which helps in maintaining thestability and efficiency of the power system.

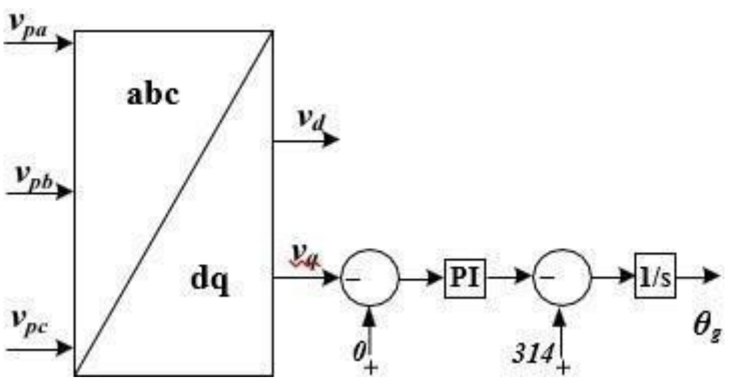


Fig.4Estimationofgridvoltagephase angle

Toestimatethegridvoltagephaseangle,youbeginbycollectingreal-timedataofthethree-phasevoltagesusingsensorsor transformers.Thisdata isthenconverted into a simpler two-phasesystem,often referredto asthe αβsystem,whichmakes the analysis more manageable. From this two-phase representation, the phase angle of the voltage waveform is calculated. Thisphaseangleindicatesthepositionofthevoltagewaveformwithinitscycle,whichiscrucialforsynchronizationtasks.

Toensurethephaseangleestimateisaccurateandstable,filteringtechniquesareappliedtoreducenoiseandfluctuations in the data.

This filtered phase angle is then used for various applications, such as synchronizing generators and power converters with the grid, thereby maintaining the stability and efficiency of the power system.

1. **MeasurementCollection**:
    - Obtainreal-timemeasurementsofthethree-phasevoltagesVaV_aVa,VbV_bVb,andVcV_cVcfromthe grid using voltage transformers or sensors.
2. **ClarkeTransformation**:
    - Convert the three-phase voltages into the two-phase stationary reference frame (αβ0) using the Clarketransformation:

$$\begin{pmatrix} V_\alpha \\ V_\beta \\ V_0 \end{pmatrix} = \frac{2}{3} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix}$$

3. **ConversiontoTwo-PhaseSystem**:Convertthethree-phasevoltagemeasurementsintoatwo-phase(αβ) system to simplify analysis. This transformation helps in processing the data more effectively.

4. **PhaseAngle Calculation**: Calculate the phase angle from the two-phase system. The phase angle represents the position of the voltage waveform in its cycle and is essential for synchronization purposes.

5. **FilteringandSmoothing**:Applyfilteringtechniquestothecalculatedphaseangletoreducenoiseandfluctuations. This ensures the phase angle estimate is stable and accurate.

III. IntroductiontoANNControllers

AnArtificialNeuralNetwork(ANN)isacomputationalmodelinspiredbythewaybiologicalneuralnetworksinthehuman brain process information. It consists of interconnected groups of artificial neurons organized in layers.ANNs are capable oflearningfromdata,adaptingtonewinputs,andperformingcomplextaskssuchaspatternrecognition,classification,and control.

ANNControllersinPowerSystems

In power systems,ANN controllers are used to enhance performance and improve power quality.The primary function of anANNcontrollerinapowersystemcontextistopredict,control,andoptimizevariousparametersandoperations.Dueto their ability to handlenon-linear relationshipsand adaptto changing conditions,ANN controllersare particularly effective incomplexanddynamicenvironmentslikephotovoltaic(PV)basedelectricvehicle(EV)chargingstationsinterfacedwith a three-phase grid.

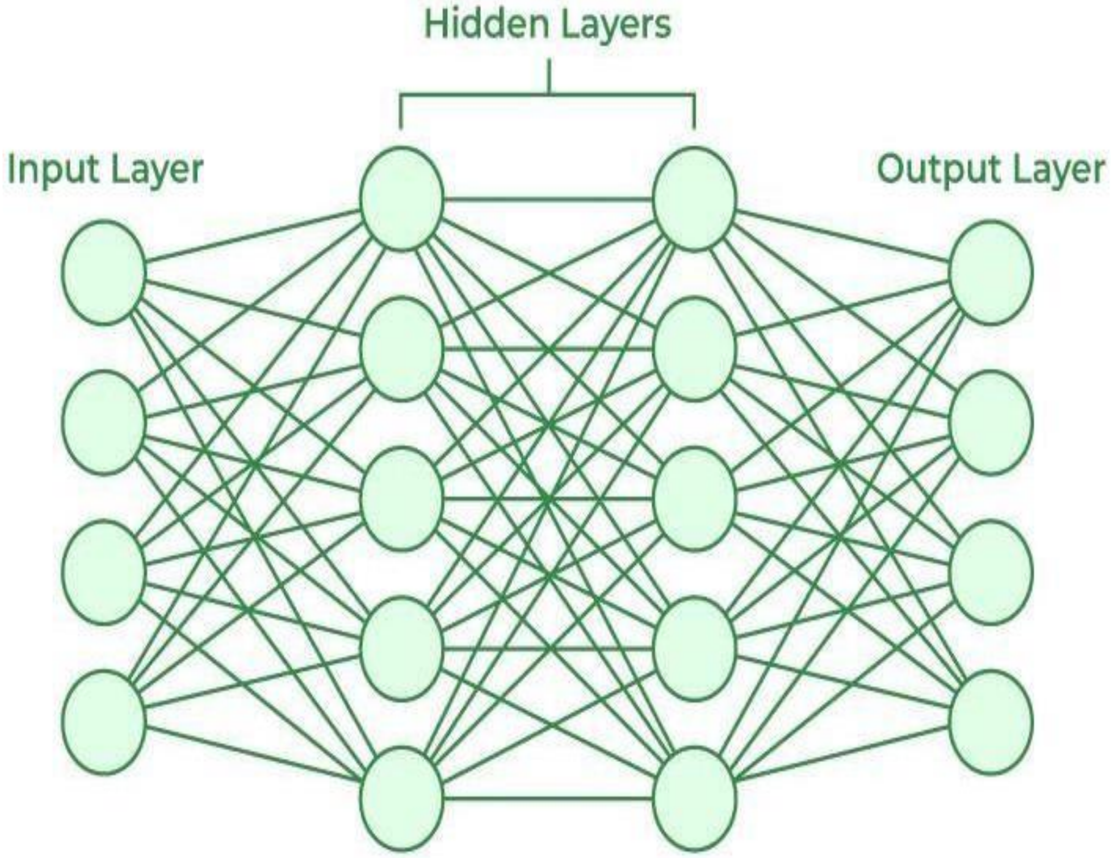


Fig.5ArtificialNeuralNetwork(ANN)

CaseStudy:ANNControllerinaPV-BasedEVChargingStation

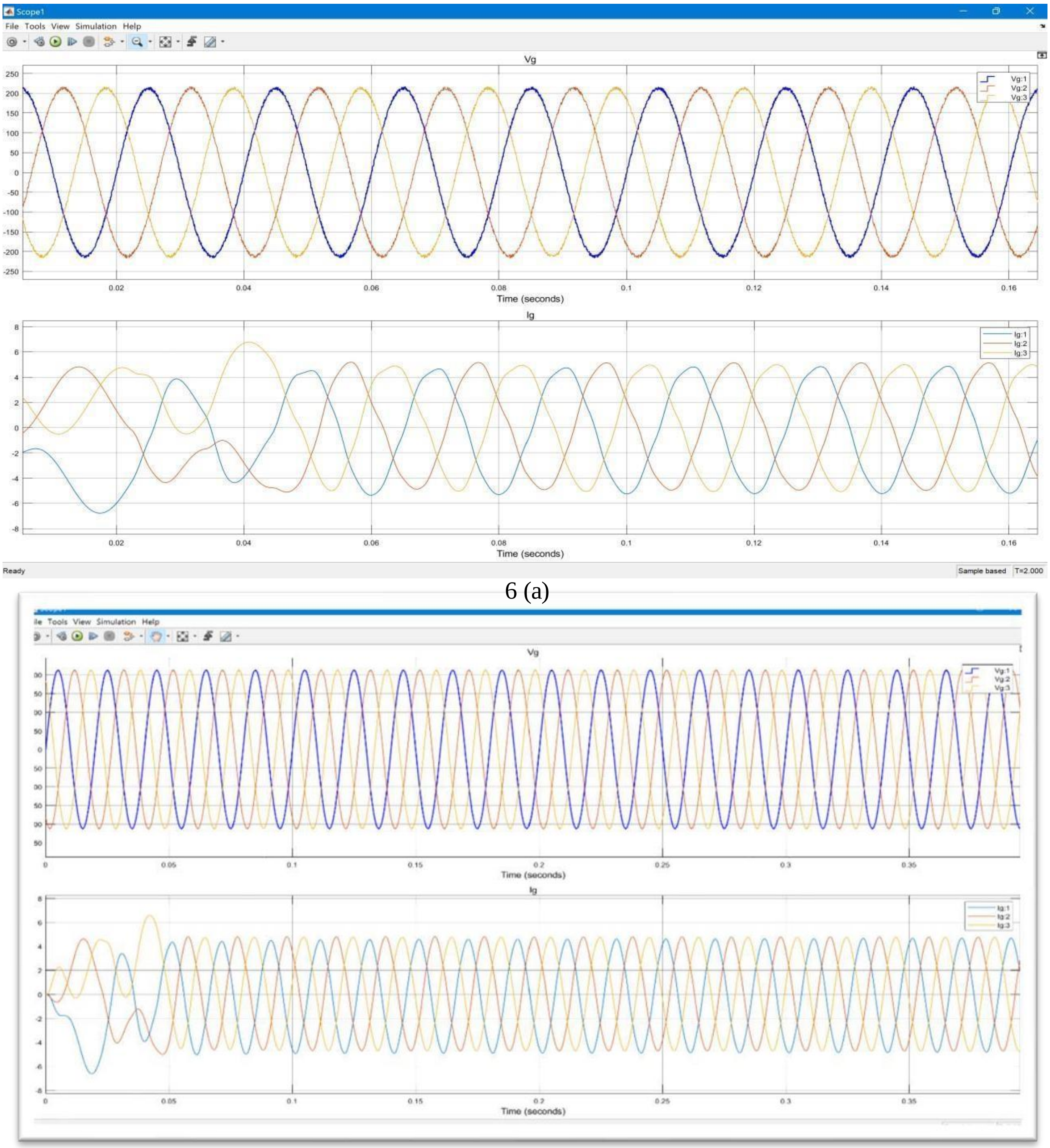
ConsideracasestudyofaPV-basedEVchargingstationimplementedwithanANNcontroller.Thechargingstationhasa capacity of 100 kW of solar panels and 20 EV chargers, interfaced with a three-phase grid. TheANN controller is trained using historical data on solar output, EV charging demand, and grid conditions. \

Results

AfterdeployingtheANNcontroller,severalimprovementsinpowerqualityareobserved:

- **Voltage Stability**:Voltage fluctuations are reduced by 30%, resulting in a more stable voltage supply to the grid and EVs.
- **HarmonicDistortion**:Harmonicdistortionlevelsdecreaseby25%duetoadaptivefiltering.
- **Frequency Stability**: Frequency variations are minimized,maintaining the grid frequency within ±0.1 Hz of the nominal value.
- **ReactivePower Balance**: Thepowerfactorimprovesfrom0.85to0.95,indicatingbetterreactivepower management.
- **Load Balancing**: Phase imbalances are reduced by 20%, enhancing the stability and efficiency of the gridconnection.

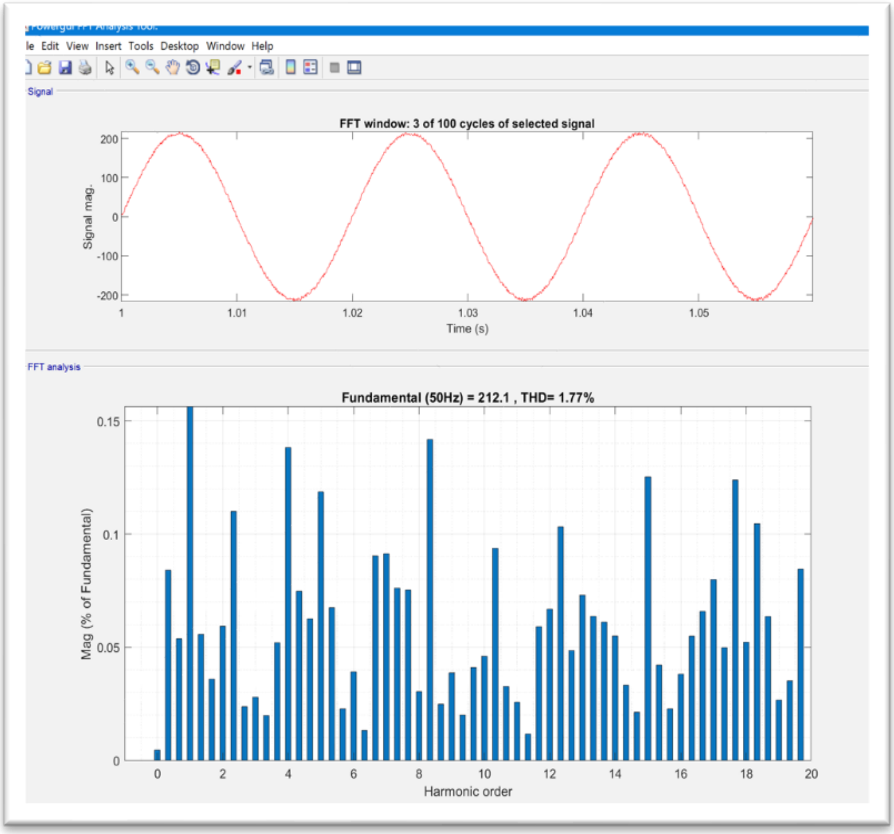
IV. *Results*



6 (a)

6 (b)

Fig.6a)PowerFlowfromPVtoGRIDUsingPIcontroller(TopvoltageBottomCurrent)b)withANN



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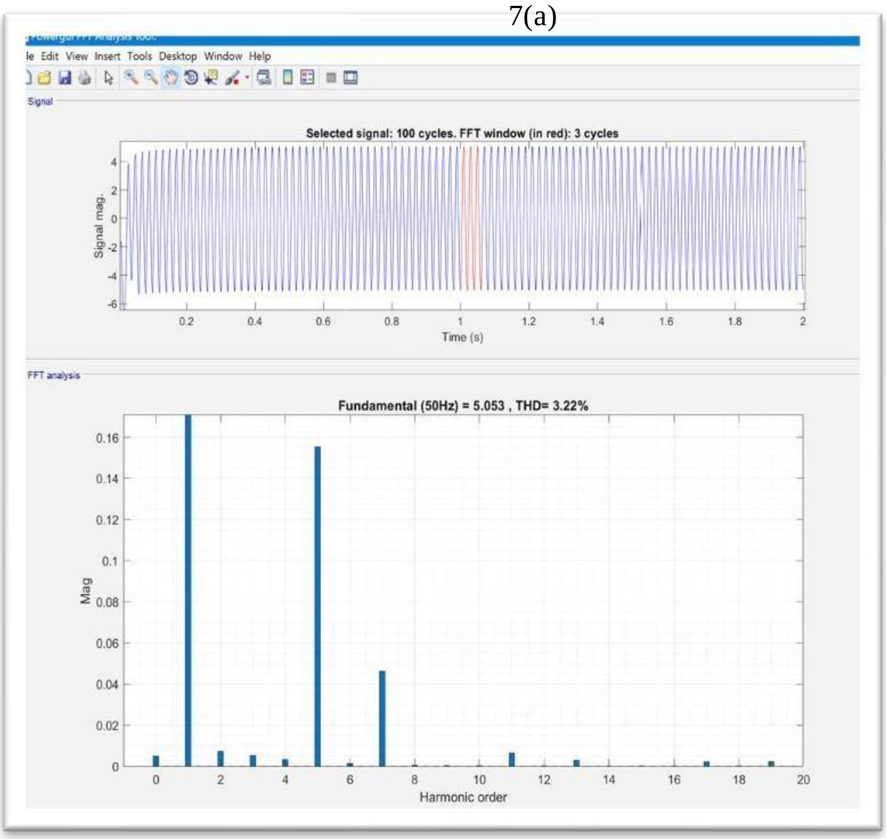
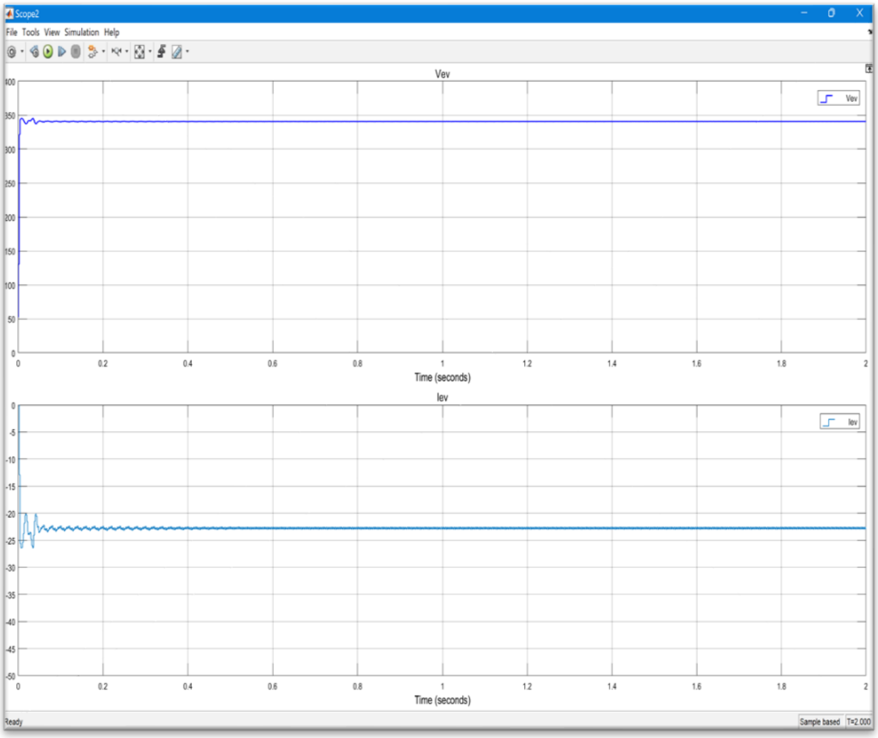
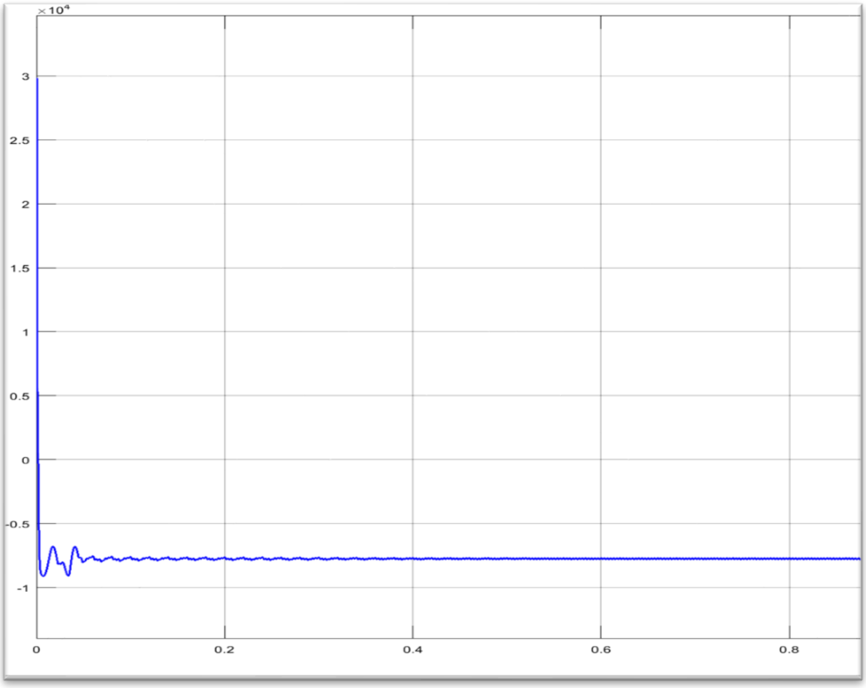


7(b)

Fig.7a)FFTanalysisofTHDwithPIa)GridVoltageb)GridCurrent



9 (a)



9 (b)

Fig.9WithANNa)ChargingstationVoltage&currentb)Chargingstationpower

V. Conclusion

AsinglestagePVbasedEVchargingstationhasbeenintendedwiththecapabilityofsynchronizationtothegrid andfeedingthepowergeneratedbythechargingstationThispaperpresentsacomprehensivestudyonpower

qualityimprovementinPV-basedEVchargingstationsinterfacedwithathree-phasegridusingahybridcontrol strategy combining a PI controller and an Artificial Neural Network (ANN). The proposed method aims to enhancethestabilityandefficiencyofEVchargingstations,addressingthecriticalissueofpowerqualityingrid-connected systems.

Keyfindingsfromtheresearchinclude:

1. **Improved Power Quality:** The hybrid PI-ANN control strategy significantly reduces Total Harmonic Distortion (THD) in both voltage and current, ensuring compliance with grid standards and improving overall power quality.

2. **EnhancedStability:**TheintegrationofANNfordynamicgainadjustmentinthePIcontrollerenhances system stability under various operating conditions, including normal operation and fault conditions.

3. **Superior Performance:** Comparative analysis with conventional fixed-gain PI control and ANN-PI control demonstrates the superior performance of the proposed hybrid method in maintaining power quality and system stability.

4. **Effective in Different Scenarios:** The proposed control strategy proves effective in various grid conditions, providing robust performance during grid-connected and standalone operations.

The contributions of this study to the field of power quality management in PV-based EV charging stations are significant, offering a viable solution for integrating renewable energy sources with the grid. However, further research is needed to explore the long-term reliability and practical implementation of the proposed method in large-scale applications. Future work should also investigate the potential of advanced machine learning techniques for further enhancements in power quality control.

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