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THREE LEVEL T-TYPE QUASI Z SOURCE PV GRID TIED INVERTER WITH ACTIVEPOWER FILTER FUNCTIONALITY UNDER RESEARCH FOCUS

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ABSTRACT

In light of the fact that the majority of power electronics utilised in photovoltaic (PV) inverters at commercial and industrialsitesbehaveasnon-linearloadsfromthegridside,thesehigh-powerthepowerqualityofthenetworkisanticipatedto besignificantlyimpactedbydemandinstallations.Thisstudyprovidesacompleteframeworktohelpwiththeirintegrationinto thedistributiongrid.Quasi-ZSourceT-TypePVinvertercontroltechniquethatusesthespareinverterpowercapacitytoexecute active and reactive power regulation, harmonic and imbalance correction, and imbalance compensation. Contrary to other methods, the one put forth here functions properly under distorted and imbalanced grid voltages. When assessing how the suggestedtechniqueworkswiththree-phasePVinverters,theelectricalnetworkarchitectureinsideacommercialandindustrial site is taken into account.

Duetothepowertopology'scapacitytoraisethevoltage, it isnot necessarytoemploythestandardstep-uptransformer and/or supplementaryDC-DCconverterfoundinPVinvertersystems.Theeffectivenessofthesuggestedtechniqueisillustratedusing a 50 kWconverter model with a disrupted grid environment and fluctuatingload conditions.

INDEXTERMS

Grid-connected PV inverters, commercial and industrial Nano grids, and reactive power compensation, compensation for harmonics and imbalance, and quasi-impedance-source T-type inverters.

I. INTRODUCTION

The aggregation of renewable energy sources (RES), particularly those that are sporadic, non-dis patchable, or unpredictable,createssignificantdifficultiesforelectricitygriddesignandoperation.ThefunctionofNanogridsinthissituation becomes crucial. Nano grids, in essence, are just tiny micro grids that typically serve one or a few buildings or facilities. CommercialandIndustrialNanogrids(CINs),whichincludefactoriesorofficebuildings,haveattractedmoreattentioninrecent years. DC voltage is produced by the majority of RES, including fuel cells and photovoltaic (PV) modules. Therefore, power producedbyRESshouldgenerallybecondition.Inthisinstance,grid-interactivePVinvertersexplicitlyperformthisprocedure, which is typically handled by power electronics systems (PVI).The traditional voltage source inverter (VSI), one of the topologies most frequently utilised in these converters, has several limitations. The DC input voltage must be greater than the peak grid voltage. The DC voltage levels generated in practical applications, such PV systems, are typically modest and subject to large variations depending on the operating circumstances. In order to raise the DC voltage, a second DC-DC converter is needed. Utilizingastep-uptransformerisanadditional alternative.Alternately,theuseofanimpedancesource(Z-source)invertercan doawaywiththeneedforbothanextraDC-DCconverterand/orastep-uptransformer.TheZ-sourcenetwork,whichismadeup of two capacitors and two inductors, connects the DC bus terminals to the inverter input. This approach allows for the employment oftheso-calledShoot-Through(ST)states,whichareutilisedtogeneratevoltageboost,inadditiontothewell-knownswitching combinations used in VSIs, which produce the so-called Non-Shoot-Through (NST) states. A topology known as a quasi- impedance source inverter (quasi-Z-source) was introduced as a further advancement. However, several studies have found advantages to using three-level inverters in PV systems. By switching only half the DC link voltage, this architecture exhibits reduced switching losses and lower harmonic contents in the output voltage than the two-level inversion one. A well-known member of this family is the neutral-point-clamped (NPC) inverter; a more recent member is the T-type inverter, which offers significantgainsoverNPCbyloweringswitchinglossesatlowerswitchingfrequencies.Anintriguingideaisthecombinationof a quasi-Z networkand a three level inverter. Morespecifically,ithas beenthought about tocombine a quasi-Z networkwith a three level T-type inverter. In any case, the majority of converters exhibit non-linear behaviour and demand distorted and unbalancedcurrents from the AC grid.As a result, acomplete installation'scurrents will bedisturbedandout of balancewhen observedfromtheACside.Gridvoltageswillbedistortedasaresultofthesecurrentdemandsandthosemadebynearbyfacilities linked to the same distribution feeder. Themajority ofPVI control solutionsin the technical literature attempt toavoid adding furtherdistortionwhileadheringtothesuggestedlimits.Nevertheless,whenthegridvoltagesaredistortedand/orimbalanced, suchsolutionsfailtofunctionproperly.Itisimportanttomentionatthispointthatelectronicpowerconvertershavethecapacity tooperateactivelyand,asaresult,canperformauxiliarytasksfortheelectricalsystem,suchasfrequencyandvoltageregulation and power quality enhancement. There are a lot of published papers on three-phase grid interactive inverters, but not many on gridinteractiveinvertersbasedonZ-sourceorquasi-Z-sourceconverters.Mostresearchonthistopologyisprimarilyconcerned withmodulationmethodsandcapacitorvoltage balance difficulties.WhilemanystudiesuseZ-sourceand2-levelVSI,references dealwith Z-Source-T-typeand quasi-Z-Source T-typetopologies,respectively, with grid controlbut donotimplement corrective measures. A grid control approach with compensating action was recently put into practise by the authors, although it has not been demonstrated that it performs well when the grid voltage is distorted.

Asaresultoftheforegoing,itisstillnecessarytoenhanceandexpandthefunctionsthatcanbeprovidedbyelectronicconverters, whichcanbedonebyresearching varioustopologiesalong withbettercontrol strategies. Thiswillhelptofacilitatetheincreasing integration of RES into the network. These are this paper's primary contributions:

1. The incorporation of PV inverters into a commercial and industrial Nano grid that is based on a three-phase Quasi-Z-Source Three-Level T-Type topology. The control strategy I integrates several functions that have been partially implemented on this particular power topology, such as active and reactive power control, harmonics and imbalance mitigation, (ii) suggests a cooperative operation between inverters inside the CIN, and (iii) in any case, performs well under distorted and unbalanced grid voltage, extending the successes reported.
2. The control strategy is simple and may be used to coordinate or operate independently to achieve harmonic and imbalance mitigation, reactive power compensation, and optimal PV power injection into the grid. Furthermore, the DC link capacitors found in PV's AC/DC converters allow them to be employed as active filters even when there isn't any sunlight. No matter what process the power electronics equipment is used in, the concept aims to maximise its benefits. The remaining parts of the essay are arranged as follows. Following the configuration of a PV-based CIN, a detailed explanationoftheinverter structure,control scheme, modulationmethod,andcurrent controller isprovided.

II. POWERSTRUCTUREANDCONTROLSYSTEM

Figure 1 depicts the structure of a typical CIN case. Using an MV/LV transformer, a total power of between 1000 and 1500kWisconnectedtotheMediumVoltage(MV)distributionnetwork.TheLowVoltage(LV)networkcontainsfourwires, threephases,and230/400V,withtheneutralgroundedatthetransformerneutralinaccordancewiththeTTgroundingscheme, and it can supply both single-phase and three-phase loads.

A. TOPOLOGY

TheproposedtopologyforPVIisdepictedinFigure2.ThisT-typeinverterfeaturesthreelevels,threephases,and a quasi-Z source. The quasi-Z network, the T-type three-level inverter, the output filter, and the DC voltage source—which represents a renewable energysource are all shown in the figure. While the currents from each individual PVI are I_A,I_B,$I_C$the voltageandcurrentfromthePVpanelsareU_{PV}andI_{PV},respectively.Figure2alsodepictstheassignedportionoftheunbalanced andnon-linearloadontheCIN(whichwillbefurtherspecified).TheCINinjectsI_{GA},I_{GB},I_{GC}totalcurrentsintothegrid,whereas this load requires I_{LA}, I_{LB}, I_{LC}total currents.

TheterminalsP,0orNareconnectedtotheoutputs(a',b',andc')oftheinverterusingvariousswitchingcombinations. The result is a waveform with three voltage values (UPN/2, 0 and UPN/2). These NST states represent the corresponding switching combinations.Theoutputiszero-voltagewhentheupper(S_1)andlower(S_2)switchesofeachphaseareclosed,joiningthePand Npoints.TheonebeingdiscussedistheaforementionedSTcondition,whichisnotallowedinaconventionalVSI(withoutthe Z-source network),becauseit causes ashort circuitinDCsource.Thedutycycleof theSTstatecan bealteredtoraisetheDC bus voltage.

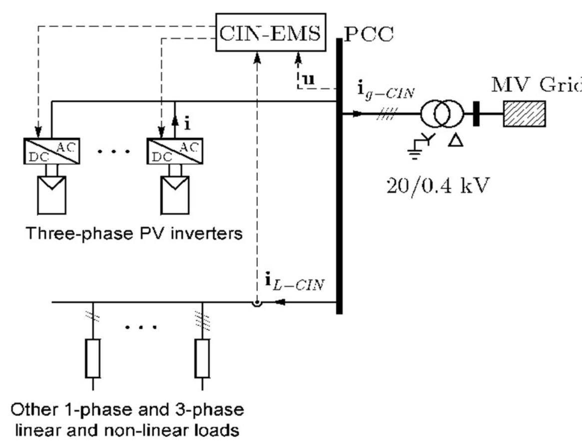

Fig.1. Photovoltaic(PV)basedCINarchitecture.

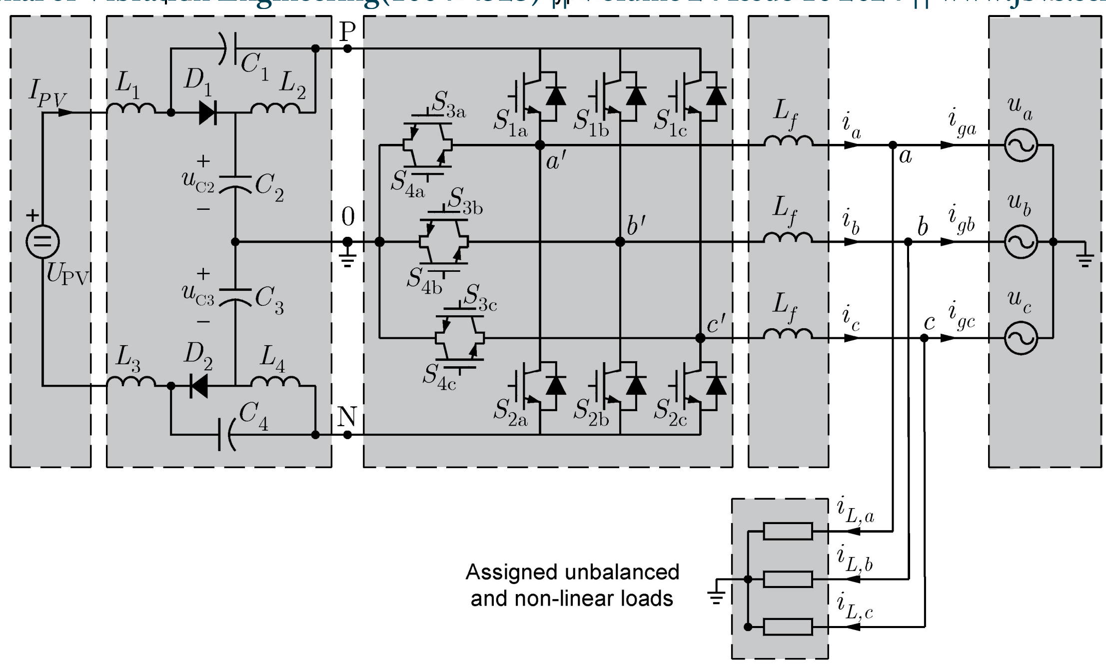

Fig.2. Three-phase topology for one PV inverter (PVI) and the assigned fraction of the facility's unbalanced and non-linear loads.

TheswitchingperiodT=TN+T0isusedtodefinethedurationsoftheNSTandSTstates,andtherelatedddutyratiosare DN=TN/T and D0=T0/T. The voltages across the passive components are uL1=uL3, uL2=uL4 and uC1=uC4, uC2=uC3 assuming thatthequasi-Z-sourcenetworkissymmetric(i.e.,L1=L3,L2=L4andC1=C4,C2=C3)Theconverterisalsosupposedtoruninc continuousconductionmode.Takingintoaccountthat,insteadystate,theaveragevoltagevalueattheinductorterminalsduring each switching period is zero. The boost factor B is defined from:

$$B = \frac{\hat{U}_{PN}}{U_{PV}} = \frac{1}{1 - 2D_0}$$

where$\hat{U}_{PN}$isthepeakDC-linkvoltage,availableduringNSTstates.
Theamplitudeofthefundamentalcomponentoftheoutputphase-to-neutralvoltageisgivenby:

$$\hat{U}_{an,1} = m\frac{\hat{U}_{PN}}{2} = m\frac{1}{1 - 2D_0}\frac{U_{PV}}{2}$$

where*m*isthemodulationindex.

B. PROPOSEDCONTROLSRATEGY

InordertoachievetheactivepowerandreactivepowersetpointsofferedbytheCIN-EMS,thereferencecurrentfor eachPVIofaCIN,$I^*=(I^*_a I^*_b I^*_c)^T$(seeFigures1and2)iscalculatedusingthecontrolstrategy.Itisalsopossibletoachieve harmonicandimbalancecompensationatthePCCifthePVIratedpowerisnotexceeded.Inordertoprovidebalancedand sinusoidalcurrentswithdisplacementpowerfactor(DPF)inaccordancewithCIN-EMScriteria,eachPVIworkstogetherto improvetheperformanceoftheLVnetwork.Withaminimumamountoferrorbetweenthemeasuredandreferencecurrents, the tracking technique obtains the switching signals for the PVI.

ThethreeelementsthatmakeupthePVIreferencecurrentvectorareactivepower$I^*_P=(I^*_{Pa} I^*_{Pb} I^*_{Pc})^T$,reactivepower $I^*_Q=(I^*_{QA} I^*_{QB} I^*_{QC})^T$,andharmonicandimbalanceloadcurrent$I^*_{HI}=(I^*_{HIA} I^*_{HIB} I^*_{HIC})^T$.Thesetermsareexplainedinmore detail in the following sections.

The block diagram of the PVI control system is shown in Figure 3, where P*and Q*1 are set by the CIN-EMS and $I_L$is determined at the PCC.

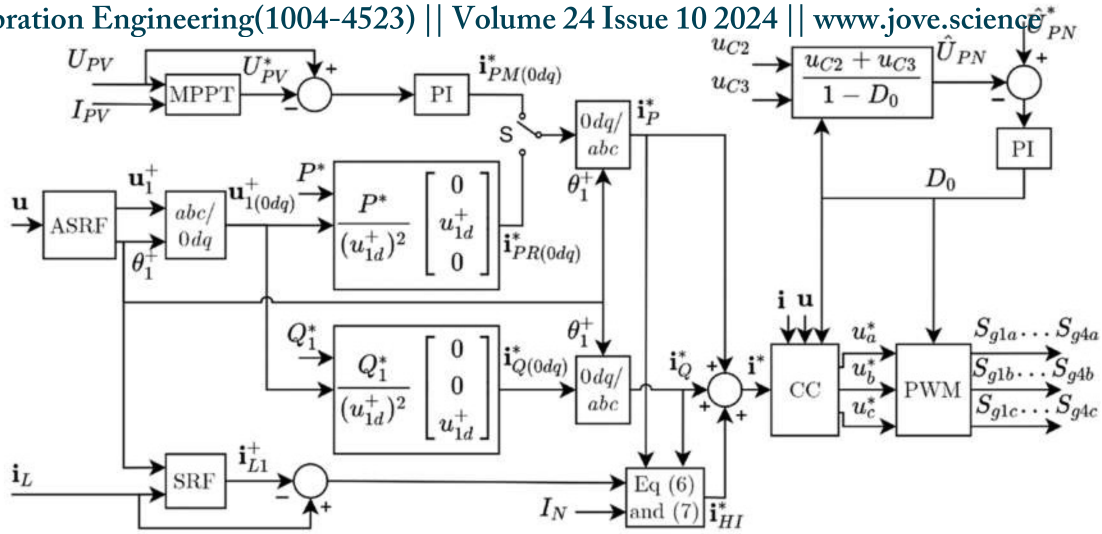

Fig.3. BlockdiagramofthePVIcontrolsystem.

C. ACTIVEPOWERCONTROL(PMODE)

Inordertomakethecurrentinjectedintothegridproportionalto the positive-sequencefundamentalgridvoltage,a modifiedversionofthePerfectHarmonicCancelation(PHC)controlapproachissuggested.ItmakessurethePVIrunsona unityDPFthatdeliverssinusoidalandbalancedcurrent.MaximumPowerPointTrackingmode(MPPTmode)andReference Power Point Trackingare thetwo operationalmodesthat aretaken intoconsiderationforthis Pmode (RPPTmode). AnMPPTalgorithm,suchasthetraditionalPerturbandObserve,willbeusedtodeterminethereferencePVIcurrentinthe 0dq reference frame when the MPPT mode is active (chosen by the switch S), based on local voltage and current measurements from the PV panels connected to the specific PVI.

However, in the RPPT mode, the CIN-EMS assigns a three-phase active power set point Pto everyindividual PVI basedonavarietyofparametersthat dependoncommercialoreconomicconsiderations,which areoutside the purviewof thisarticle.Toprovidesomeexamplesinthisareamightbefascinating,though.Therefore,theRPPTmodecouldbeusedif the inverter briefly stops producing power and makes use of all of its capabilities to function as a static synchronous compensator (STATCOM), as suggested in. Additionally, if a PVI is connected to an energy storage system, such as one basedonbatteries,thesystem mayinject a reference constant activepower into thegridperiodically.

Ifthebatteriesarefullychargedandthesolarirradiationistoogreatinthissituation,itmaybenecessarytolimitthe powerfromthePVpanels.ThereferencePVIcurrentinthe0dqreferenceframeisderivedinthisstudyfromthepreviously mentioned reference power set point P* by the following current vector when the RPPT mode is engaged (chosen by the switch S in Figure 3).

$$\mathbf{i}^*_{PR(0dq)} = \frac{P^*}{(u^+_{1,d})^2}\begin{bmatrix}0\\ u^+_{1,d}\\ 0\end{bmatrix},$$

Apositive-sequencefundamentalvector,U_1+,anditsphaseangleareextractedfromthegridvoltageUviaanAuto-Adjustable SynchronousReferenceFrame(ASRF) phaselocked-loop.Afterthat,thePark transformationisappliedbythe block abc/0dq.

D. REACTIVEPOWERCONTROL(Q-MODE)

Reactive power management or PCC voltage support may be offered by the CIN for commercially viable reasons based ontariffincentives.Thus,theCIN-EMStransmitstoeachuniquePVIafundamentalthree-phasereactivepowersetpointQ_1*. The fundamental reactive power flowfromthegridtothe PVI(Q_1*<0)andthe fundamentalreactive powerflowfromthe PVIto the grid (Q_1*>0) are thetwo operational modes that aretaken intoconsideration.

A proposed control approach that derives from the PHC strategy tries to have the PVI deliver balanced current that is sinusoidalandlags90degreesafterthegridvoltage'spositive-sequencefundamentalcomponent.Asaresult,thereference PVI current in Q mode is determined as follows in the 0dq reference frame:

$$\mathbf{i}^*_{Q(0dq)} = \frac{Q^*_1}{(u^+_{1,d})^2}\begin{bmatrix}0\\ 0\\ u^+_{1,d}\end{bmatrix}$$

Likewise, the reference current vector in the abc frame $I_Q^*$is obtained by means of the inverse transformation 0dq/abc.

E. LOADCURRENTHARMONICSANDIMBALANCEREDUCTION(HIMODE)

Thismodeseekstobalancetheunbalancedandharmoniccurrentsrequiredbythe CINloadssuchthatthePVIactsas anActivePowerFilter(APF).Thisresultsinimprovedpowerqualityandimbalanceratiosinthe CINduetotheinvolvement of all PVIs. The CIN-EMS computes portions (i_L) for each PVI based on the total load current at the PCC ($\mathbf{i}_{L-CIN}$), which is measured and divided by the CIN-EMS. While this is going on, the phrases below can be used to dissect the load current assignedtoaPVI.ATotalHarmonicandImbalanceCompensation(THIC)controlstrategyisproposedaimingthatthePVI current isequal and opposite to theharmonic and fundamental unbalancedcomponentsof I_L, that is:

$$\mathbf{i}_{HI}^{*} = -(\mathbf{i}_L - \mathbf{i}_{L1}^{+})$$

Byutilisingthepositive-sequencefundamentalphaseanglesuppliedbytheASRFblock,theSynchronousReference Frame (SRF) block is responsible for extracting i_{L1}+ from the allocated load current vector i_L. In order to prevent the PVI from exceeding its nominal current i_N, the reference current in Equation (5) must be saturated. As a result, the reference current's Root Mean Square (RMS) value for the HI mode is determined to be

$$I_{HI,\max} = \sqrt{I_N^2 - I_P^2 - I_Q^2}$$

where $I_P$and $I_Q$are the RMS values for I_P* and I_Q*, respectively. Finally, the reference PVI current is obtained from the equations below.

$$\mathbf{i}_{HI}^{*} = -(\mathbf{i}_L - \mathbf{i}_{L1}^{+}) \qquad \text{if } I_{HI} \leq I_{HI,\max}$$
$$\mathbf{i}_{HI}^{*} = -(\mathbf{i}_L - \mathbf{i}_{L1}^{+})\frac{I_{HI,\max}}{I_{HI}} \qquad \text{if } I_{HI} > I_{HI,\max}$$

whereisthehighestRMSvalueofthecomponentsofI^*_{H1}.ThepartthatperformstheTHICstrategyappearsatthebottomof Figure 3.

F. CURRENTCONTROLLERANDMODULATIONMETHOD

Acurrentcontroller(blockdesignatedCCinFigure3)willbeutilisedafterthecurrentreferenceshavebeendefined tomakesurethattheinverteroutputcurrentsfollowthosereferences.Tocontrolthepresenterror(deltaI)astraightforward proportionalcontrollerischosen.Thisproportionalcontrollerisactuallysettochangethedesiredmaximumcurrentripple, whichisexpressedasapercentageofthenominalcurrent.BytakingintoaccounttheconstraintU_Y*<1-D_0,whereystands forthephasea,b,orc,asaturationblockrestrictsthemaximumandminimumvaluesofthecontrolsignals.Inthepartsthat follow, a precise and quick transient response of this controller with no steady error will be demonstrated. This is the implementation block diagram is represented in figure 4.

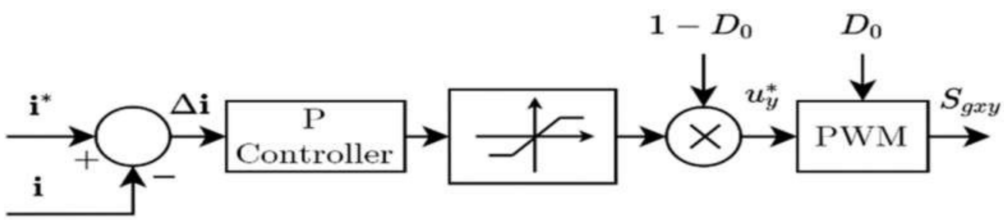

Fig.4. Blockdiagramofthecurrentcontrollerandmodulator

ThedutycycletobeusedoneachbranchofthenetworkisdeterminedbyeachsignaldenotedasU_Y*aninverter.Aswitched dutycycleisreachedbecausethiscontrolactioniscomputedasaproportionalvalueofthedifferencebetweenthemeasured **I**andtheinstantaneousreferenceI*(withaswitchedform),asshowninFigure5.Thedifferentgatesignals(S_{gxy}),wherex representstheswitch(1,...,4)forthepowerconverter,arethengeneratedusingalevel-shiftedpulsewidthmodulation(LS- PWM) in phase disposition with constant boost control (CBC).

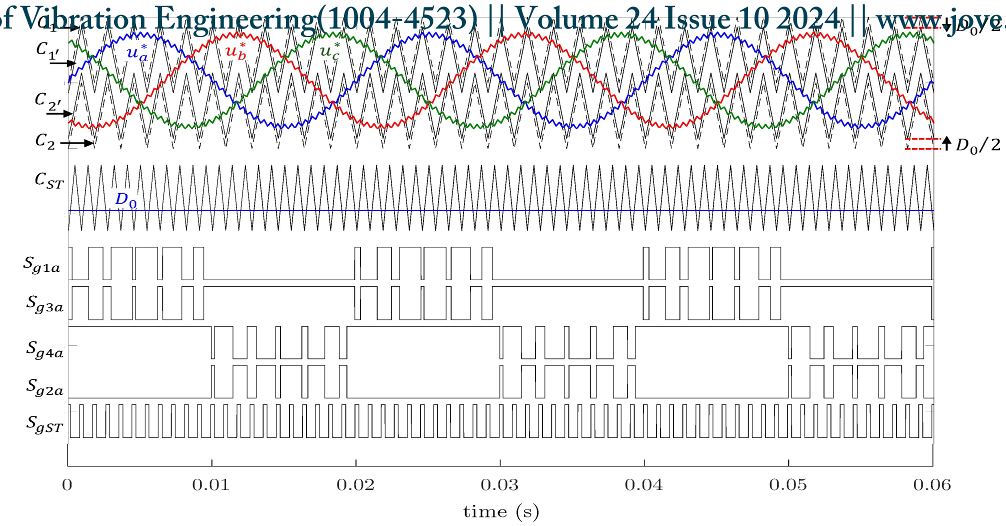

Fig.5.Switchingsignalgenerationwiththelevel-shiftedpulsewidthmodulation(LS-PWM)inphasedisposition with the constant boost control (CBC) scheme.

The layout of the LS-PWM in phase arrangement with CBC is shown in Figure 5. For better viewing, a frequency modulation index of 11 has been employed. To create the NST states and activate the various power switches, the three signals U^*_y and two carrier signals (upper [0, 1] and bottom [-1, 0]) are compared. The NST states for branch a, for instance, are showninthesameimage.In reactiontotheSTstate generationindicatedbyD$_0$, anothercarrier withadoublefrequencyis present.WhentheSTstatesaregeneratedinthismanner,theyareuniformandhaveaconstantwidthduringthebasicperiod. Finally,carriers C_1andC_2areshifted.Thevalueof $D_0/2$tocompensatetheoutputaveragevoltagewhichisaffecteddueto ST states insertion.

G. DCBUSVOLTAAGEREGULATION

ThepeakvoltageU$^*_{PN}$inZ-sourceinvertersistheDC-linkvoltagethatispresentduringNSTstates.Bymodifying D_0inaccordancewithequation(1),thevariablePVvoltageUPVvalue—whichisbroughtaboutbychangesinsolarirradiance orreferencepower—canbecontrolled.TheDC-linkvoltageisapulsedvoltagewaveform,henceitmustbekeptinmindthatit cannotbeutilisedasafeedbacksignal.So,adeceptivestrategyisused.ThevoltagesofcapacitorsC$_1$,C$_2$,andC$_3$aremeasured, and the following relationis used tocompute the actual peak DC-link voltage:

$$\bar{u}_{C2} + \bar{u}_{C3} = (1 - D_0)\hat{U}_{PN}.$$

ThedifferencebetweenthereferencemagnitudeU$^{\wedge*}_{PN}$andtheestimatedmagnitudeU$^*_{PN}$isseeninFigure3'stopright corner.TheSTduty-cycleD$_0$isthenproducedbyprocessingtheerrorsignalbyaProportionalIntegral(PI)controller.The PWM stage's input consistsof thisduty cycle and the output ofthecurrent controller.

III. SIMULATIONRESULTSANDANALYSIS

The current studyis concentrated on PVI power rangeof 50-200 kW, which is suitable for commercial,industrial, andmulti-megawattPVsystems.APVIwiththefollowingrating,moreparticularly,istakenintoaccount:230/400V;50Hz, 50kW.A72.5ratedRMScurrentisthecorrespondingvalue.ThekeyequipmentspecsareincludedinTable1.According to the followingequationswere used to determine the source network's component parts:

$$C_{1,4} \geq \frac{2P_{out}(1 - 2D_0)}{U_{PV}^2 f_{sw} K_C} \tag{9}$$

$$C_{2,3} \geq \frac{2P_{out}(1 - 2D_0)D_0}{U_{PV}^2 f_{sw} K_C (1 - D_0)} \tag{10}$$

$$L_{1,2,3,4} \geq \frac{U_{PV}(1 - D_0)D_0}{2I_{PV} f_{sw} K_L (1 - 2D_0)} \tag{11}$$

Alongwiththepreviouslymentionedvariables,thefollowingtermsareusedintheseequations:F_{SW},K_L,istheassumed ripplein I_{PV}, $P_{out}$is the rated output power,and KC, isthemaximumvoltage rippleacross thecapacitors.

AnoutputfiltermadeupoftheinductorsL$_f$reducestheoutputvoltageharmonicdistortionattheswitchingfrequency. Thevaluesoftheseinductorsarederivedusing[36]fromtheequationbelow.

$$L_f \geq \frac{U_{inv}(h_{sw}) \cdot U_g}{2\pi f_1 \cdot h_{sw} \cdot P_{out} \cdot THD_I}, \quad (12)$$

where $U_G$is the RMS grid voltage (phase-to-neutral), F1 is the fundamental frequency, $H_{SW}$is the switching harmonic order, THD1istheanticipatedtotal harmonicdistortionoftheoutputcurrent,and$U_{INV}(H_{SW})$isthedesiredharmonicdistortionofthe output voltage at the switching frequency.

OtherthanthePVIsthemselves,anequivalentloadrepresentingofthelinearandnon-linearloadsontheCINistakeninto account.Thisload'sratedapparentpowerrequirementoughttoberoughlyequaltothetotalinstalledPVpowerintheCIN.Asa result,theCINcouldruninoff-gridmode.TheCIN-EMSmeasurestheCIN'sloadcurrent(I_{L-CIN})atthePCCandgiveseachPVI a fraction(I_L). Harmonic analysis andtheaccompanying correction procedures, accordingtocommercial buildingsandindustrial plants,arenecessarywhenasignificantamountofnon-linearloads(usuallylargerthan25%to30%ofthetotalload)isalready presentorispredictedtobeadded.Therefore,harmonicandimbalancecorrectionoveraround40%oftheentiredemandforthe CINissuggestedinthisworkasarepresentativeexample.Asaresult,theloadRMScurrentassignedtoaparticularPVIwillbe roughly 40% of the PVI's rated RMS current, I_L=30 A in this case.

Table1. Mainparametervaluesforthe3-phasePVI

PARAMETER	VALUE	UNIT
InductorsL_1,L_4	0.5	MH
CapacitorsC_1,C_4	2.2	MF
L_f	0.75	MH
Voltageoutputfilter	800-1100	V
U_G	230	V
KLandKC(outputvoltage)	0.05	P.U.
$U_{INV}(H_{SW})$	0.05	P.U.
THD1	0.05	P.U.
PoweroutputratingP_{out}	50	KW

The PSCAD simulation programme has been used to create a simulation model for a PVI under the aforementioned conditions. With a simulation time step of 10^{-6} s, the switching frequency and sampling rate were both set to 10 kHz. It was intendedforthefour-wireLVnetworktobeimbalancedanddistorted.Whilethepercentagesforharmonics5and7arecomputed forhavingaTotalHarmonicDistortion(THD)withinthe8%limit,theindividualdistortionpercentageforharmonic3ischosen atitsmaximumlevel.Thezero-sequencecomponent()isaddedwiththeinversesequencecomponent()setatitsmaximumvalue. Table 2 displays these numbers.

Table 2. Low Voltage (LV) network characteristics.

Voltage Harmonic Distortion (%)			Voltage THD (%)	U^-/U^+ (%)	U^0/U^+ (%)
HD3	HD5	HD7			
5	4.5	4	7.83	2	2

U^+,U^-,U^0: positive-, negative- and zero-sequence fundamental components.

Figures6to10showtheoutcomesofthesimulation.WithtwodistinctPVvoltagesstartingatt=0,thesimulationbegins undertwodifferentsolarirradiationcircumstances.U^{*}_{IN}=1060VischosenasthenecessaryDClinkvoltage.TheSTcontrol and thethree control modes(P,Q, and HI)areturned on at t =0.2 s. Considered are thecases listedbelow.

- CaseA.PVvoltagesettoU$_{PV}$=1060V.MPPTmode.P*=50kW;Q_1^*=0;CINloadwithoutharmonics orimbalance; injecting active power close to rated power with no reactive power.
- Case B: RPPT mode with PV voltage set to U_{PV}=850 V. Active and reactive power injection: P* = 45 kW; Q_1^*= 21.7 KVAR. CIN's load is unbalanced and harmonic-free.
- Case C: RPPT mode with PV voltage set to U_{PV}=850 V. Active and reactive power injection: P* = 45 kW; Q_1* = 15 KVAR. The maximum load for CIN with odd harmonic currents is the ninth order. Table 3 displays harmonic and imbalancecontent.Accordingtostandardcalculations,thecorrespondingcurrent'sRMSvalueforthisloadisI_{LE}=31.53 A.ThepurposeofHIcompensationisnotactivated.
- CaseD:RPPTmode,PVvoltagesettoU =850V.injectingP*=45kWofbothactiveandreactiveelectricity;Q_1*=15 KVAR. Harmonic andunbalancedloadcharacteristics ofCINas ininstance C. TheHI compensating feature is turned on.

- CaseE.RPPTmode.PVvoltagesettoU$_{PV}$=850V.Activeandreactivepowerinjection P*=45kW;Q$_1$*=21.7KVAR; respectively.ContentoftheCIN'sloadthatisharmonicandunbalanced,asinexamplesCandD.TheHIcompensation feature is active.

InsituationsA(Figure6)andB(Figure7),theCINloadcurrentissinusoidalandbalanced,hencethereference currentfortheHIcontroliszero.InexampleA,theCIN-EMSdoesnotsupplyareactivepowersetpoint;asaresult,the MPPTalgorithmjustactivatesthePcontrolwithareferencevalue.Byinjectingacurrentintothegridinphasewiththe positive-sequencefundamentalgridvoltage,thePVIachievesaunityDPF.InscenarioB,theCIN-EMStransmitsactive andreactivepower setpointstothePVI.TheDC-linkvoltageisneartoitsreferencevalueinbothscenarios,ascanbe shown.

Table 3. Harmonic content of the Commercial and Industrial Nanogrids (CIN) current for cases C-E.

Individual Harmonic Distortion (% Respect to the Positive-Sequence Fundamental Component)				Total Harmonic Distortion THD (%)	I^-/I^+ (%)	I^0/I^+ (%)
HD3	HD5	HD7	HD9			
21.6	10.7	7.2	3.8	25.44	10	10

I^+, I^-, I^0: positive-, negative- and zero-sequence fundamental components.

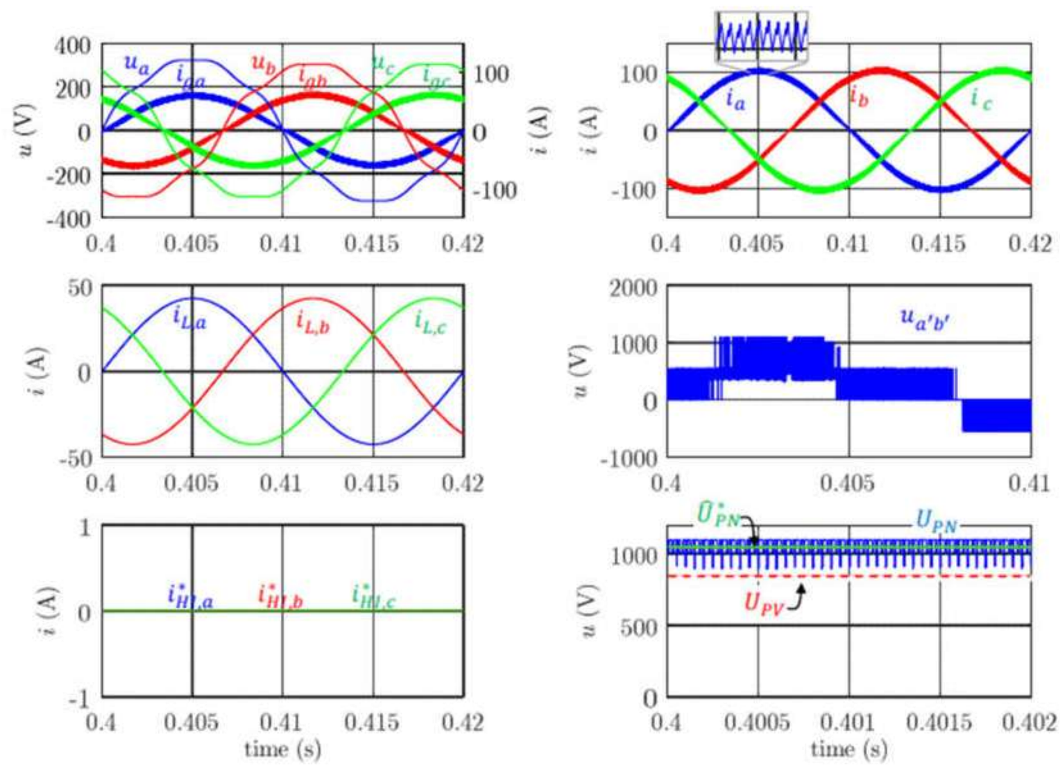

Figure6.Simulationoutcomes.CINsetpoints(deliveredatt=0.2s)inCaseA:CINloadwithnoharmonicsorunbalance,and P*= 50kW:I$_L$=30A.Lefttorightandtoptobottom,respectively:gridded voltages(U$_A$,U$_B$,U$_C$), grid currents(I$_{GA}$,I$_{GB}$,I$_{GC}$), PVIoutputcurrents(I$_A$,I$_B$,I$_C$),loadcurrents(I$_{LA}$,I$_{LB}$,I$_{LC}$),phase-to-phasePVIoutputvoltagebeforefiltering(U$_{A'B'}$),harmonics andimbalancecorrectionPVIreferencecurrents(I*$_{HI,A'}$I*$_{HL,B'}$I*$_{HL,C'}$),aswellasPVvoltage(U$_{PV}$),DC-linkvoltage(U$_{PN}$),and reference DC-link voltage (U^*$_{PN}$).

The CIN load current is imbalanced (I^-/I^+= 10%, I^0/I^+ = 10%) and distorted (see Table 3) in example C (Figure 8). The gridcurrentisoutofbalanceanddistortedbecauseinthissituationtheHIcompensatingmechanismisnotengaged.Table4lists the load, grid, and PVI phase currents' harmonic and imbalance components.

Image7.Simulationoutcomes.CaseB.ThevaluesareP*=45kWandQ$_1$*=21.7KVAR,respectively.TheCINloadisI$_L$=30A. from top to bottom and left to right, as shown in Figure 6.

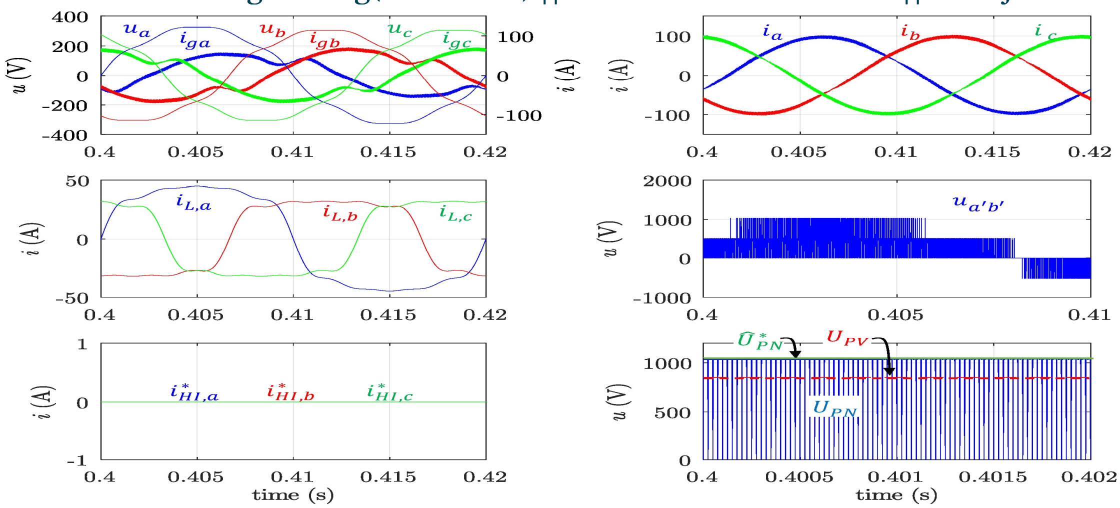

Figure8: Simulationoutcomes.CaseC.CINloadwithharmoniccomponentsdefinedinTable4withP*=45kWand=Q_1*=15 KVAR. from top to bottom and left to right, as shown in Figure 6.

InCaseD(Figure9),theHIfunctionisengagedeventhoughtheCINloadcurrentisdistortedandimbalancedjustlikein CaseC.ItispossibletoobtainbalancedsinusoidalgridcurrentssincetheCIN-EMSsetpoints andcompensationrequirements areconsistentwiththePVInominalcurrentandtheconverterisabletocompleteitsassignedtasks.Table5liststheload,grid, andPVIphasecurrents'harmonicandimbalancecomponents.THDinloadcurrents,ascanbeobserved,rangesfrom21-28%;in contrast,THDingridcurrentsisnoticeablylowerataround5%.Unbalancesareconcerned.TheloadcurrentsI-andI0areeach decreased to0.14and 0.2 Ain thegridcurrents,respectively,fromtheir original values of I^-=3Aand I_0= 3 A.

Table 4. Harmonic and imbalance components of load, grid and PVI currents for case C.

Current	Harmonics							Imbalance	
	I_1 (A)	I_3 (A)	I_5 (A)	I_7 (A)	I_9 (A)	I (A)	THD (%)	I^- (A)	I^0 (A)
$i_{the\_}$	36	6.48	3.21	2.16	1.14	36.80	21.20		
i_{Lb}	27	6.48	3.21	2.16	1.14	28.06	28.27	3	3
i_{Lc}	27	6.48	3.21	2.16	1.14	28.06	28.27		
i_{ga}	37.59	7.02	3.66	2.54	1.16	38.56	22.92		
i_{gb}	45.19	6.88	3.62	2.56	1.14	45.97	18.79	3.26	3.19
i_{gc}	45.25	6.84	3.59	2.53	1.16	46.03	18.65		
i_a	68.59	0.54	0.45	0.38	0.02	68.61	3.04		
i_b	69.21	0.41	0.41	0.40	0.01	69.23	3.00	0.26	0.19
i_c	69.25	0.36	0.38	0.37	0.04	69.27	2.97		

$I_1 \ldots I_9$: RMS harmonic components; I: RMS total. I^-,I^0: negative- and zero-sequence RMS fundamental component.

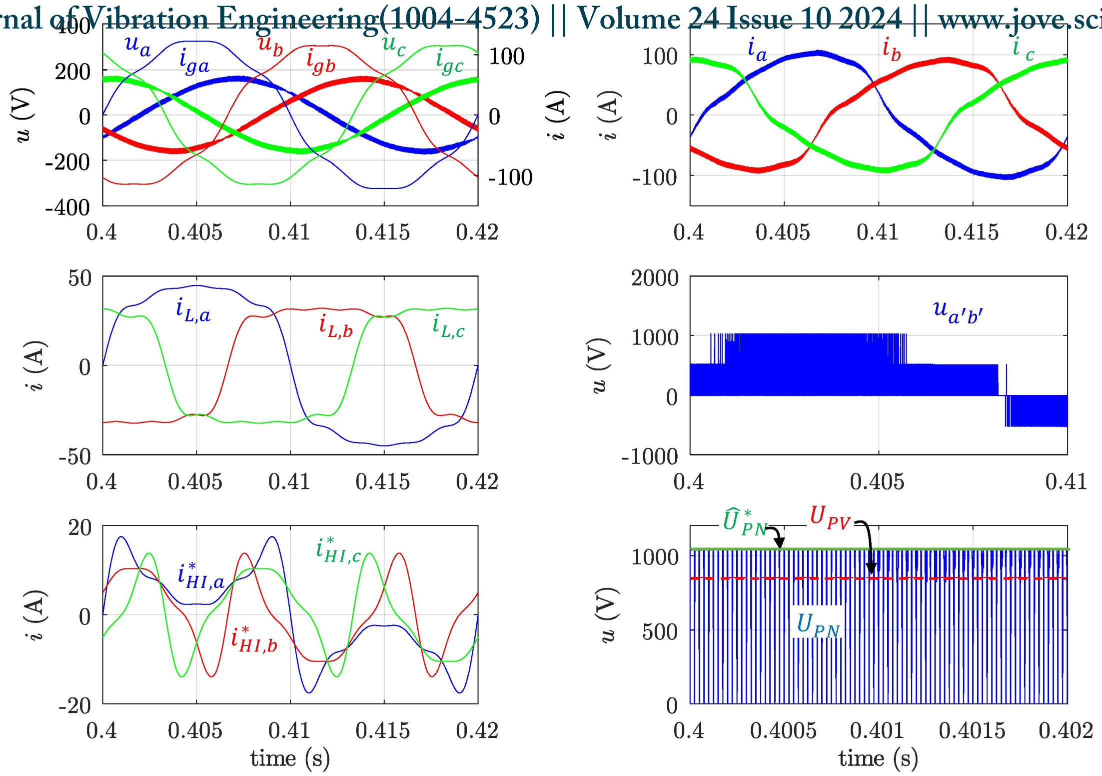

Figure 9. Results of the simulation. Case D. A CIN load with harmonic and unbalanced components as stated in Table 3 with P*= 45 kW and Q1*= 15 KVAR. as in Figure 6, from top to bottom andleft to right.

Table 5. Harmonic and imbalance components of load, network and PVI currents for case D.

Current	Harmonics							Imbalance	
	I_1 (A)	I_3 (A)	I_5 (A)	I_7 (A)	I_9 (A)	I (A)	THD (%)	I^- (A)	I^0 (A)
$i_{the\_}$	36	6.48	3.21	2.16	1.14	36.80	21.20		
i_{Lb}	27	6.48	3.21	2.16	1.14	28.06	28.27	3	3
i_{Lc}	27	6.48	3.21	2.16	1.14	28.06	28.27		
i_{ga}	42.89	0.32	0.15	0.15	0.20	42.93	4.60		
i_{gb}	42.39	0.41	0.15	0.18	0.21	42.43	4.80	0.14	0.20
i_{gc}	42.47	0.46	0.15	0.21	0.18	42.51	4.82		
i_a	74.96	6.72	3.17	2.10	1.29	75.39	10.75		
i_b	66.04	6.88	3.20	2.05	1.31	66.54	12.43	3.13	3.20
i_c	66.10	6.88	3.18	2.06	1.28	66.60	12.41		

Asin Cases CandD, Case E(Figure 10) exhibits the same distortionand unbalance of the CINloadcurrent whilealso activatingtheHIfunction.However,thereactivepowerhasbeenraisedto21.7KVARfromtheactivepowersetpointof45kW. When using these values, it is impossible to satisfy the compensation needs without overloading the machinery. Since grid currents are neither sinusoidal nor balanced,thePVI conductsa partial adjustment. Theload, grid,andPVI phase currentsfor Case E's harmonicandimbalancecomponentsarelistedinTable6.THDattheworstphaseisapproximately7.5%,andI^-andI^0are1.81 and 1.91 A, respectively, according to grid currents, which may be observed.

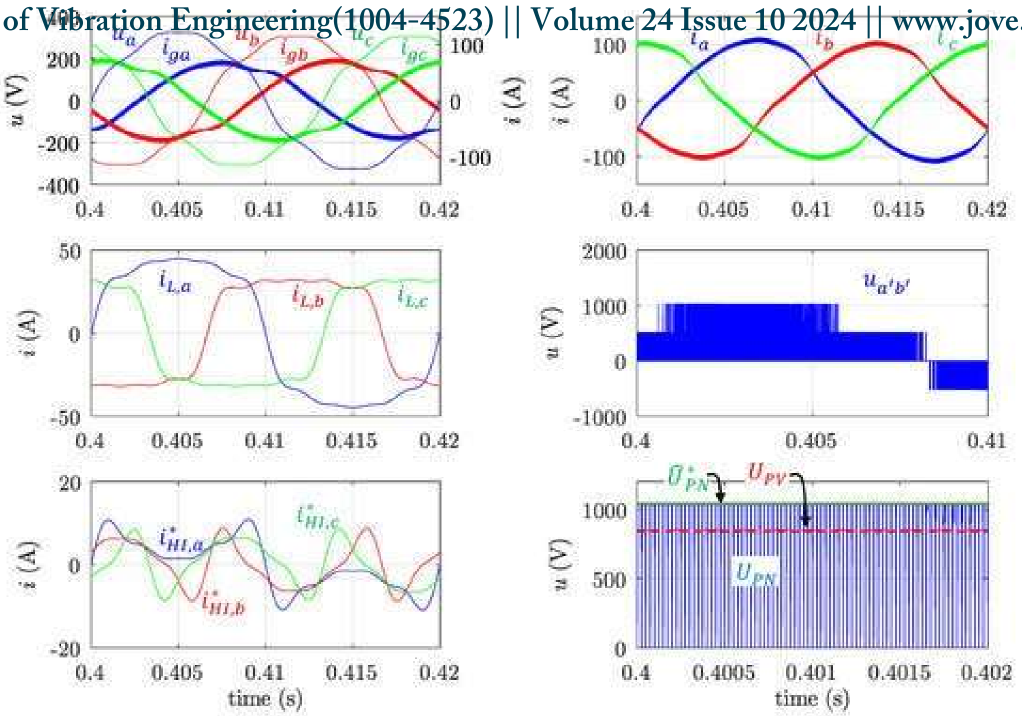

Figure10.Resultsofthesimulation.CaseEisaCINloadwiththesameharmonicandunbalancedcomponentsasCaseD,but with values of P*=45 kWand Q_1*=21.7 KVAR. as inFigure 6, from top to bottom andlefttoright.

Table 6. Harmonic and imbalance components of load, network and PVI currents for case E.

Current	Harmonics							Imbalance	
	I_1 (A)	I_3 (A)	I_5 (A)	I_7 (A)	I_9 (A)	I (A)	THD (%)	I^- (A)	I^0 (A)
$i_{the\_}$	36	6.48	3.21	2.16	1.14	36.80	21.20		
i_{Lb}	27	6.48	3.21	2.16	1.14	28.06	28.27	3	3
i_{Lc}	27	6.48	3.21	2.16	1.14	28.06	28.27		
i_{ga}	48.32	2.51	1.41	0.98	0.41	48.45	7.49		
i_{gb}	50.50	2.35	1.34	1.03	0.36	50.62	6.95	1.19	1.09
i_{gc}	50.56	2.37	1.42	1.09	0.39	50.68	7.07		
i_a	76.91	3.97	1.80	1.18	0.75	77.06	6.46		
i_b	71.97	4.13	1.89	1.14	0.79	72.15	7.13	1.81	1.91
i_c	71.98	4.12	1.79	1.08	0.76	72.15	7.05		

NumerousPVIthree-phasepowernumbershavebeendeterminedbasedonthedefinitionssuggestedinStandardIEEE-1459:2010[41].ResultsforinstancesAthroughEaresummarisedinTable7.Thepowertermslistedbelowaredisplayed:real powerSinkVA,realpowerPinkW,andrealpowerbasicreactivethedisplacementpowerfactorDPF,powerfactorPF,power Q1 in KVAR, and inactive power N in kVA.

Table7. PowertermsaccordingtoIEEE-1459:2010.

CASES	S(KVA)	P(KW)	Q1(KVAR)	N(KVA)	PF	DPF
A	50.48	50.09	0.757	6.28	0.99	0.99
B	51.03	44.13	25.07	25.62	0.86	0.87
C	47.86	44.22	17.55	18.30	0.92	0.93
D	49.13	44.73	17.54	20.25	0.91	0.93
E	51.45	44.40	25.08	26.00	0.86	0.87

Figure11illustratesthebehaviourunderseveralsetpointsettings.Thetotalperformanceisdetailedbelow:

PVIisturnedonatt=0.2sandbeginstoinject30kWfromthePVpanelsunderaparticularirradiationcondition.TheQ functionisturnedon at thesametime toinjectfundamental reactive power inthe range of one-third of theactive power, or 10 kVArinthisinstance.Althoughthegridvoltageisunbalancedanddistorted,thePVIoutputcurrentwaveformsarebalanced, sinusoidal, and trailafter the primarycomponent of phase voltage. The currentsfedintothegridareimbalancedanddistorted, though, as a result of the distorted load current.

When the PV voltage reaches 850 V at time t = 0.24 s, the DC-link voltage is controlled to its reference level (U^{*}_{PN}= 1050V),changingtheSTratioD_0.InboththeSTandNSTU^PNstates,voltageU_{PN}iszero."hasbeenupdatedtoreflectthese changes.

TheactivationoftheHIfunctioncausesthePVIcurrentstobecomedistortedandunbalancedatt=0.26s,whilethegrid currents remain sinusoidal and balanced. Due to the fact that the PVI rated power is not attained in this instance, entire compensation is feasible.

TheactiveandreactivepowersetpointsareraisedtoP*=45kWandQ_1*=21.795KVAR,respectively,att=0.32s.The technology onlyconductsapartialcorrectioninthissituation,whichleavesthegrid currents slightly distortedandout of balance.

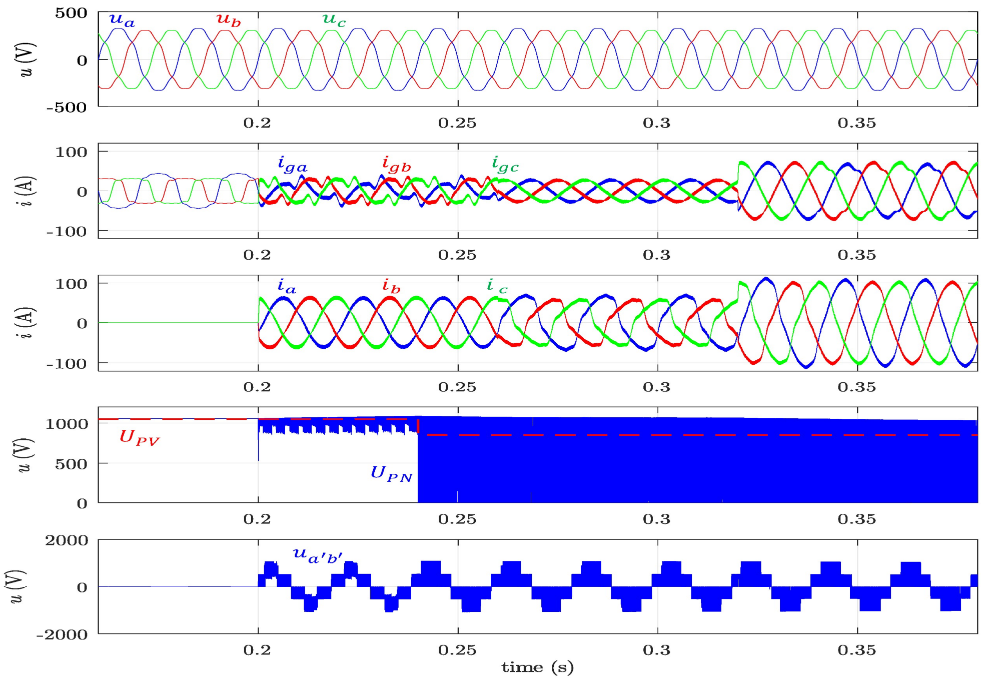

Figure11.Behaviorunderchangingsetpointconditions.Fromtoptobottom:gridvoltages(U_A,U_B,U_C);gridcurrents(I_{GA},I_{GB}, I_{GC});PVIoutputcurrents(I_A,I_B,I_C);PVvoltage(U_{PV}),DC-linkvoltage(UPN);andphase-to-phasePVIoutputvoltagebefore filtering ($U_{A'B'}$).

The actual electrical models that served as the foundation for the implemented model included accurate power stage specifications. Fuji's 12MBI100VN-120-50 IGBT T-typemodule's datasheet was used toget a few IGBTs' key specifications. Using Tustin's technique, the transfer functions and the controllers have both been constructed in their discrete form, and all measurements are sampledbefore processing at a rate of 10 kHz. This shedslight on how practically feasible the plan is when made with today's quick microcontrollers.

IV. CONCLUSION

Acontrolstrategyhasbeenpresentedforphotovoltaicconvertersthatallowsthecontroloftheoverallactiveandreactive poweroftheCINwheretheyareintegrated.Additionally,iftheconverterhassparecapacity,thecontrolstrategycontributesto reducetheharmoniccontentandimbalancesinthethree-phasecurrentsdemandedbytheentireCINatthepointofconnectionto the distribution network.

An interactivegridinverter isa three-phase Quasi-Z-Source Three-Level T-Type. This architecturehas the potential to boost voltage and does away with the need for an extra DC-DC converter and/or a step-up transformer, both of which are frequentlyseeninPVinvertersystems.Thistopology'sapplicabilityisthereforemoreeffectiveformediumfrequencyoperation than the other traditional two-level and three-level inverter architectures.

Based on the set points obtained from the CIN-EMS, it has been shown through simulation results that the reference currents can be computed locally in a time frame appropriate for practical operation, and that the currents supplied by the PVI accuratelymatchthesereferences.EveninthepresenceofdistortedandimbalancedLVgridcircumstances,properfunctioning has been accomplished.

No cross-coupling interaction was seen, showing that the controls for active power, reactive power, and harmonic imbalancealloperateseparatelyfrom oneanother.This highlights anotherbenefitofthesuggestedglobalcontroltechnique.

A laboratory scaled prototype is now being built, despite the implemented simulation's high level of accuracy, in order to empirically support the suggested control techniques on this topology.

ThesuggestedPVIsystems'actualapplicationinCINs willadvancetheaimsofthesmartgridbyenablingthedistributionsystem operator tooffer ancillary services and enhancing the LV network's power quality.

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