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REVIEW ARTICLE

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MITIGATION OF VOLTAGE SAG FOR PQ IMPROVEMENT USING A NINE-SWITCH INTEGRATED POWER CONDITIONER WITH FUZZY CONTROLLER

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ABSTRACT

Unified power quality control was widely studied by many researchers as an ultimate method to improve the power quality .In this project we can used as a nine-switch power converter is an UPQC.It having two sets of output terminals was recently proposed in place of the traditional back-to-back power converter that uses 12 switches in total. The nine-switch converter has already been proven to have certain advantages, in addition to its component saving topological feature, using fuzzy logic controller to compensate the voltage sag and swell ,the harmonic current and voltage and control the power flow and voltage stability and reduce its switching losses, an appropriate discontinuous modulation scheme is proposed and studied here in detail to doubly ensure that maximal reduction of commutations is achieved. The nine-switch converter is shown to favorably raise the overall power quality inexperiment, hence justifying its role as a power conditioner at a reduced semiconductor cost.

Key Words: Discontinuous pulse-width modulation, nine switch converter, power conditioner, power quality,UPQC

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INTRODUCTION

Static power converter development has grown rapidly with many converter topologies now readily found in the open literature. Accompanying this development is the equally rapid identification of application areas, where power converters can contribute positively toward raising the overall system quality [1], [2][3]. In addition, they need tobe programmed with voltage, current, and/or power regulationschemes so that they can smoothly compensate for harmonics, reactive power flow, unbalance, and voltage variations. For even more stringent regulation of supply quality, both a shunt and a series converter are added with one of them tasked to perform voltage regulation, while the other performs current regulation.Almost always, these two converters are connected in a backto- back configuration [1][2][5], using 12 switches in total and sharing a common dc-link capacitor, as reflected by the configuration drawn in Fig. 1(a). Even though facing no major operating concerns at present,improvements through topological modification or replacement of the back-to-back configuration to reduce its losses, component count, and complexity would still be favoured, if there is no or only slight expected tradeoff in performance.

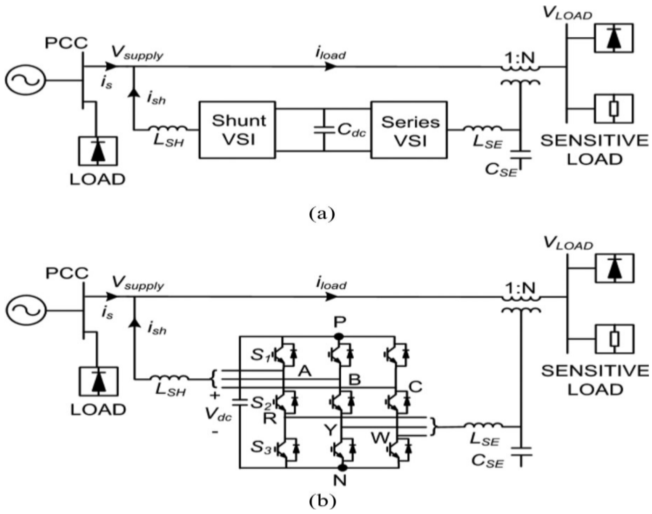

Fig. 1. Representations of (a) back-to-back and (b) nine-switch power conditioner

A classical alternative that can immediately be brought out for consideration is the direct or indirect matrix converter, where 18 switches are used in total. That represents six switches more than the back-to-back configuration, but has the advantage of removingthe intermediate electrolytic capacitor for compactness and lifespan extension. Presenting a better reduced semiconductor alternative for highquality series–shunt compensation, this paper proposes a single stageintegrated nine-switch power conditioner, whose circuitconnection is shown in Fig. 1(b). As its name roughly inferred,the proposed conditioner uses a nine-switch converter with twoSets of output terminals, instead of the usual 12 switch back-to back converter. The nine-switch converter was earlier proposedin [2][13] and [14] at about the same time, and was recommendedfor dual motor drives [13][14] rectifier–inverter systems, and uninterruptiblepower supplies [15]. More importantly, a much larger dc-link capacitance and voltageneed to be maintained, in order to produce the same acvoltage amplitudes as for the back-to-back converter.

Such replacementwill limit the full functionalities of the nine-switch converter, as explained in Section II where the nine switch converter is chosento replace a shunt and a series converter found in an integratedpower conditioner, instead of two shunt converters. Underlyingoperating principles are discussed comprehensively to demonstratehow such "series–shunt" replacement can bring forth thefull advantages of the nine-switch converter, while yet avoidingthose limitations faced by existing applications.

II. SYSTEM DESCRIPTION AND OPERATING PRINCIPLES OF ANINE-SWITCH POWER CONDITIONER

A. Back-to-Back Converter Limitations and Recommendation

Fig. 1(a) shows the per-phase representation of the common back-to-back unified power quality conditioner (UPQC), where a shunt converter is connected in parallel at the point-of common- coupling (PCC), and a series converter is connected in series with the distribution feeder through an isolation transformer. The shunt converter is usually controlled to compensate for load harmonics, reactive power flow, and unbalance, so that a sinusoidal fundamental current is always drawn from the utility grid, regardless of the extent of load nonlinearity. Complementing, the series converter is controlled to block grid harmonics, so that a set of three-phase fundamental voltages always appears across the load terminals. Rather than the described, theinverse assignment of functionalities with the shunt converterregulating voltage and series converter regulating current is alsopossible.Being so flexible, the UPQCis indeed an excellent "isolator," capable of promptly blocking disturbances from propagating throughout the system. Despite its popularity, the back-to-back UPQC is nonetheless still complex and quite underutilized, even though it offers independent control of two decoupled converters. Its underutilization is mainly attributed to the series converter, whose output voltages are usually small, since only small amount of grid harmonics need to be compensated by it under normal steady-state conditions, especially for strong grids (*V*SUPPLY=*V*LOAD). where it is stated that the converter modulation ratio can be as low as 0.05 × 1.15 with triple offset included, if the converter is sized to inject a series voltage of 1.15 p.u. during sag occurrence. Such a low modulation ratio gives rise to computational problems, but not its topological underutilization aspect.Resolving the topological aspect is, however, not so easy,Especially for cases where the dc-link voltage must be sharedand no new component can be added. Tradeoffs would certainlysurface, meaning that the more reachable goal is to aimfor an appreciable reduction in component count, while yetnot compromising the overall utilization level by too much.Offering one possible solution then, this paper presents an integratedpower conditioner, implemented using the nine-switchconverter documented in [2][13], [14], rather than the traditionalback-to-back converter. Before the nine-switch converter can beinserted though, its impact should be thoroughly investigatedto verify that there would not be any overburdening of systemimplementation cost and performance.

B. Nine-Switch Converter Operating Principles and Existing Constraints

As illustrated in Fig. 1(b), the nine-switch converter is formedby tying three semiconductor switches per phase, giving a totalof nine for all three phases. The nine switches are poweredby a common dc link, which can either be a micro source or acapacitor depending on the system requirements under consideration.

TABLE I: SWITCH STATES AND OUTPUT VOLTAGES PER PHASE

S_1	S_2	S_3	V_{AN}	V_{RN}
ON	ON	OFF	V_{dc}	V_{dc}
ON	OFF	ON	V_{dc}	0
OFF	ON	ON	0	0

The last combination of connecting its upper terminal to *N* and lower terminal to *P* is not realizable, hence constituting the first limt is nonetheless not practically detrimental, and can be resolved bycoordinating the two modulating references per phase, so thatthe reference for the upper terminal is always placed above thatof the lower terminal, as per the two diagrams drawn in Fig. 2.Imposing this basic rule of thumb on reference placementthen results in those gating signals drawn in Fig. 2 for the threeswitches of *S*1 ,*S*2 , and *S*3 per phaseEquations for producingthem can also be explicitly stated as

$$s_1 = !\ s_1{}^1 = \begin{cases} ON\ if\ upper\ reference\ is\ larger\ than\ carrier \\ \qquad OFF\ otherwise \end{cases}$$

$$s_3 = !\ s_3{}^1 = \begin{cases} ON\ if\ lower\ refrence\ is\ smaller\ than \\ \qquad carrier \\ \qquad OFF\ otherwisse \end{cases}$$

Where is the logical XOR operator. Signals obtained from(1), when applied to the nine-switch converter, then lead tothose output voltage transitional diagrams drawn in Fig. 2 forrepresenting *VAN* and *VRN* per phase. Together, these voltagetransitions show that the forbidden state of *VAN* = 0V and*VRN* = *V*dc is effectively blocked off. The blocking is, however,attained at the incurrence of additional constraints limiting the reference amplitudes and phase shift. These limitations areespecially prominent for references having sizable amplitudesand/or different frequencies, as exemplified by the illustrativecases shown in Fig. 2(a) and (b). In particular, Fig. 2(a) showstwo references of common frequency limited in their phase displacement,while Fig. 2(b) shows two references of differentfrequencies limited to a maximum modulation ratio of 0.5 each,extendible by 1.15 times if triplen offset is added, in order toavoid crossover.Considering now the second limitation detailed in Fig. 2(b),a helpful example for explaining it is the nine-switch dual drivesystem proposed in [2] [14], where references used for modulationcan have different operating frequencies. These references are for the two output terminal sets of the nine-switch converter,tied to separate motors operating at approximately the same rated voltage but at different frequencies. The maximum modulation ratio allowed is therefore 0.5 × 1.15 per reference. Even though technically viable, such sharing of carrier is not practically favourable, since to produce the same output voltages, the dc-link voltage maintained, and hence semiconductor stress experienced, must at least be doubled.

$S_2 = s_1^{\ 1}$

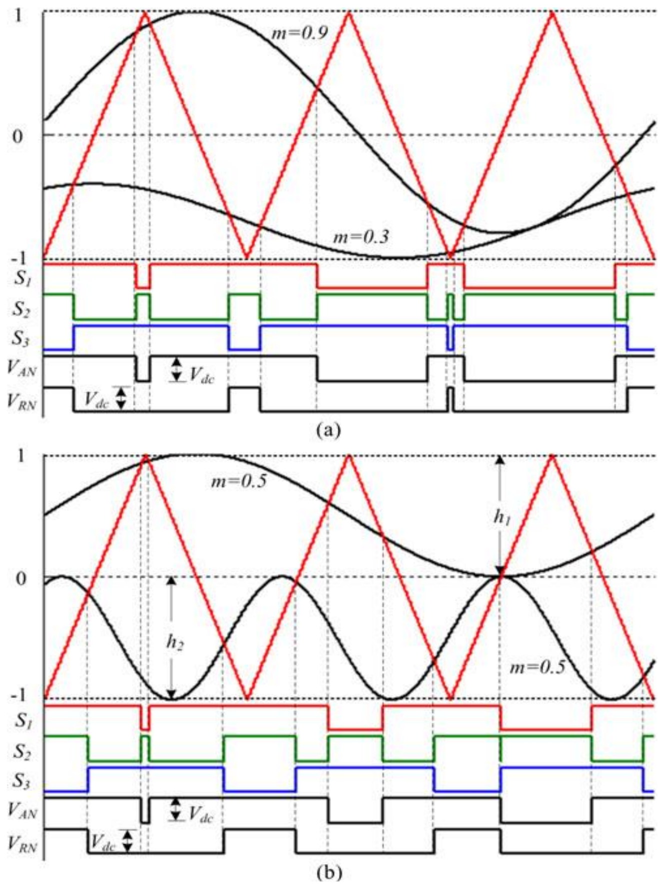

Fig. 2. Arrangements of references having (a) the same frequency but differentamplitudes, and (b) different frequencies but the same amplitude.

C. Proposed Nine-Switch Power Conditioner

Under normal operating conditions, the output voltage amplitudeof the shunt converter is comparatively much larger thanthe voltage drop introduced by the series converter along thedistribution feeder.. Drawing these details in the carrier range would then result in a much wider vertical range *h*1 in the left diagram of Fig. 3 for controlling the upper shunt terminal, and a narrower *h*2 for controlling the lower series terminal $(h_{1} \gg h_{2})$ Other operating details like logical equations used for generatinggating signals for the three switches per phase wouldremain unchanged, as per (1).For *h*2 , a comment raised here is that it can be set to zero,if an ideal grid with no distortion and rated sinusoidal In that case, the lowest three switches, labelled as*S*3 for each phase in Fig. 1(b), should always be kept ON toshort out the series coupling transformer, and to avoid unnecessaryswitching losses. If desired, the series transformer canalso be bypassed at the grid side to remove unwanted leakagevoltage drop without affecting the compensating ability of theshunt converter.

Referring back to the *h*1 and *h*2 carrier band division shownin the left illustration of Fig. 3, it would still need a higherdc-link voltage as a tradeoffs in the UPQC, but the increase ismuch reduced, and definitely not anywhere close to doubling.Quoting [2] [16] as an example, where a modulation ratio of theseries converter can be as low as 0.05 × 1.15 with triplen offsetincluded, the increase in dc-link voltage is merely about5%, before the same maximum shunt voltage amplitude, like ina back-to-back converter, can be produced by the nineswitchconverter. This maximum is however arrived at a reduced maximummodulation ratio of 0.95 × 1.15, instead of 1.15 withtriplen offset considered.

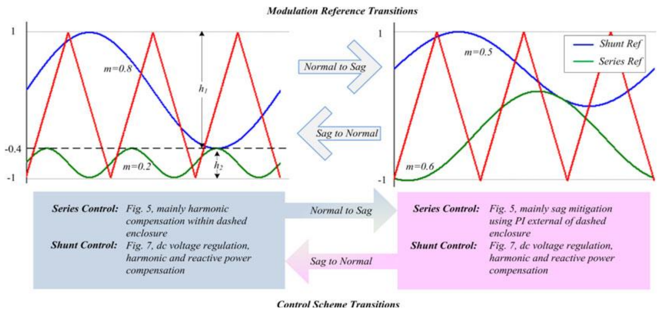

Fig. 3. Transitions of modulating references and control schemes between normal (left) and sag mitigation (right) modes.

Yet another issue to address, before the nine-switch convertercan be confirmed as a favourable topology for the “series–shunt”power conditioner, is to study its compensating ability undervoltage sag condition. For that purpose, the PCC voltage inFig. 1(b) is assumed to dip by some amount, which would thensubject the higher shunt terminal of the nine-switch converterto a reduced voltage level. The lower series terminalmust respond immediately by injecting a sizable series voltage at the fundamental frequency ($V_{SERIES} = V_{LOAD} - V_{SUPPLY}$,where $V_{LOAD}$is the demanded load voltage reference), so as tokeep the load voltage close to its Perrault value.Fig. 3 with the sameearlier mentioned phase-shift limitation imposed. Fortunately,this limitation will not hinder the operation of the nine-switchconditioner, since large injected series voltage with a demandingphase shift is usually accompanied by a severe sag at the PCC,and hence a much reduced shunt modulating reference. Thecompressed shunt reference would then free up more carrierspace below it for the series reference to vary within, as easilyperceived from the example drawn on the right of Fig. 3.The function of unified power quality controller is to mitigate the disturbence that affects the performance of the critical load

In conclusion, the proposed nine-switch power conditionercan indeed operate well under both normal and sag operatingconditions, owing to its auto complementary tuning of shuntand series references within the single common carrier band.Suitability of the nine-switch converter for “series–shunt” replacementis therefore established without any stringent practicallimitations encountered, unlike those existing “shunt–shunt”replacements.

III. PER UNIT COMPARATIVE DETAILS

Section II-C provides a qualitative justification for using thenine-switch converter as a UPQC or other series–shunt conditioners.This justification is now reinforced here by some numericalvalues calculated for determining the semiconductorlosses and component ratings of the back-to-back and nine switchpower conditioners.

For the latter, it is further dividedinto three subcategories without modifying the context of series–shunt power conditioning. The following now describes each ofthe four cases in detail, before summarizing their features.

A. Back-To-Back UPQC

Back-to-back UPQC allows independent control of its shuntand series converters, and hence does not need to divide itscarrier band into two, like in Fig. 3. That means $h2$ is zero,and its dc-link voltage can be set to the minimum of Vdc−BB =2√ 2/1.15 p.u. (subscript BB stands for “back-to-back”), if thenominal RMS grid voltage is chosen as the base. Voltage ratingsof the dc-link capacitor, series and shunt switches would thushave to be higher than this value, after adding some safetymargin. Current rating of the series switches also has to be higherthan (1 + k) p.u., after adding some safety margin, and treating

TABLE-II: P.U. COMPONENT RATINGS AND LOSSES NORMALIZED TO NOMINAL GRID VOLTAGE AND LOAD CURRENT

UPQC TYPE	Capacitor Voltage Rating	Semiconductor Voltage Rating	Semiconductor Current Rating	Total Semiconductor Losses (Conduction & Switching)
		*** With Series Compensation ***		
Back-to-Back UPQC	$2\sqrt{2}/1.15$	$2\sqrt{2}/1.15$	$1+k$	4.62% Normal; 5.40% Sag[1]
Proposed Nine-Switch UPQC	$1.05 \times 2\sqrt{2}/1.15$	$1.05 \times 2\sqrt{2}/1.15$	$1+k$	3.24% Normal; 5.19% Sag[1]
Nine-Switch UPQC with Equally Divided Carrier	$2 \times 2\sqrt{2}/1.15$	$2 \times 2\sqrt{2}/1.15$	$1+k$	9.26% Normal; 11.27% Sag[1]
		*** Without Series Compensation ***		
Back-to-Back UPQC	$2\sqrt{2}/1.15$	$2\sqrt{2}/1.15$	$1+k$	0.62% Normal; 5.40% Sag[1]
Nine-Switch UPQC with CF Control	$2\sqrt{2}/1.15$	$2\sqrt{2}/1.15$	$1+k$	0.71% Normal; 4.94% Sag[1]

[1]Evaluated with a 40% in-phase sag

B. Proposed Nine-Switch UPQC

As shown in Fig. 3, the proposed nine-switch UPQC operateswith its carrier band divided into $h1$ and $h2$. The latter, beingmuch narrower, is for blocking small grid harmonic voltagesfrom propagating to the load, is only about 5% of the full carrier band. The minimumdc-link voltage, and hence voltage ratings of components, mustthen be chosen based on Vdc-NS = 1.05 Vdc-BB, where SubscriptNSis used to represent “nine-switch.” Current rating wise, analysisof the nine-switch UPQC is slightly different, because of itsmerging of functionalities to gain a reduction of three switches.Focusing first at the upper $S1$ switch, maximum current flowingthrough it would be the sum of shunt ($-k$) and series (1 +k) currents per phase when $S1$ and $S2$ are turned ON, and hencegiving a final value of 1 p.u. Being slightly higher, the commonmaximum current flowing through $S2$ and $S3$ is (1 + k) p.u.,which flows when $S1$ and $S2$ are turned ON for the former, and$S1$ and $S3$ are turned ON for the latter. Note, however that thesemaximum currents are only for sizing the switches, and shouldnot be exclusively used for computing losses. The reason wouldbe clear after considering $S1$ as an example, where it is notedthat the maximum current of 1 p.u. does not always flow. In fact,when $S1$ and $S3$ are turned ON, the current flowing through $S1$ issmaller at $-k$ p.u., whose duration depends on a number of operatingparameters like modulation ratio, phase displacement, andothers. Analytical computation of losses is therefore nontrivial,as also mentioned in [2] [13], whose simulation approach is nowpracticed here for computing the UPQC losses. Obtained resultsfor both normal and sag operating modes are subsequentlysummarized in Table II for easier referencing.

C. Nine-Switch UPQC with Only Common Frequency Control

Reactive power compensation is one of the common yet very important issues for power system engineers at transmission as well as distribution level.This load- reactive powemand level is mainly affected by the type of loads present on the network.The capacitor banks have been used to compensate the load- reactive power demand.The traditional way certain major disadvantages such as fixed compensation possible occurence of reasonance condition with near byloads,switchingtransient,bulkysize,aging effect, etc Nine-switch UPQC, constrained to operate with the samecommon frequency (CF) at its shunt and series terminals, is not able to compensate for harmonic grid voltages.Whoseeffect is a minimum dc-link voltage that is no different fromthat of the back-to-back UPQC. The series transformer, beingno longer used, can also be bypassed to avoid unnecessary leakagevoltage drop, and to divert the large load current away fromthe UPQC, leaving the three switches per phase to conditiononly the $-k$ shunt current. Among the switches, the lowest $S3$switch behaves differently in the sense that it is always turnedON, as explained in Section II-C, and therefore produces onlyconduction losses. It will only start to commutate when a sagoccurs, and the transformer exists its bypassed state. When thathappens, the load current again flows through the switches,inferring that their current rating must still be chosen above(1 + k) p.u., as reflected in Table II, together with some calculatedloss values.

D. Nine-Switch UPQC with Equal Division of Carrier Band

Although not encouraged, the nine-switch UPQC can alsobe implemented with its carrier band divided into two equalhalves, like the different frequency mode studied previouslyin [12]–[14]. The maximum modulation ratio per reference isthen 0.5 × 1.15, whose accompanied effect is the doubling of mdc-link voltage and switch voltage rating without affecting their corresponding current rating. Such doubling is of course undesirable,which fortunately can be resolved for UPQC and otherseries–shunt applications, by simply dividing the carrier bandappropriately with *h*1 being much wider than *h*2 , instead ofmaking them equal. Results for the latter, although not recommended,are still added to Table II for comprehensiveness.

E. Comparative Findings

Analyzing all results tabulated in Table II, it is clear that the higher voltage requirement of the nine-switch UPQC can be as much as doubled, if not implemented correctly. This doubling can fortunately be reduced by narrowing the half, labelled as *h*2 in Fig. 3, to only 5%of the full carrier band. Another observation noted is the slightly lower losses of the nine-switch UPQC, as compared to its back-to-back precedence, when both schemeshave their series compensation activated. The same lower lossesare also observed with voltage sagmitigation, but not with equalcarrier division.The former leads to a smallerdc-link voltage, while the latter causes losses to be smaller, sincelarge load current now does not flow through the nine-switchUPQC. For comparison, values calculated for the back-to-backUPQC operating without series compensation are also included,which clearly show it having slightly lower losses under normal Operating condition. [2] The lower losses here are attributed tothe back-to-back UPQC using only six modulated switches forshunt compensation, while the nine-switch UPQC uses six uppermodulated switches (*S*1 and *S*2 per phase) and three lowerconducting switches (*S*3). This finding would reverse when sagoccurs, during which the back-to-back UPQC uses 12 modulated Switches, while the nine-switch UPQC uses only nine,and hence producing lower losses.

IV. MODULATION AND CONTROL

Upon verifying its appropriateness, suitable modulation andcontrol schemes are now presented for controlling the nineswitchUPQC with reduced switching losses and roughly thesame performance standards as its back-to-back counterpart.Relevant details for attaining these goals are presented shortlyin Section IV-A–C.

A. Modulation Principles

Because of its independency, modulation of traditional back to-back converter can be performed with its two sets of three phasereferences centrally placed within the vertical carrier span.Performance quality obtained would then be comparable to theoptimal space vector modulation (SVM) scheme. in Section II-B. Obtaining optimal waveformquality at both terminals of the nine-switch converter is, therefore,not possible, but is not a serious limitation theFig. 4. 120◦-discontinuous references with (a) *MSH* = *MSE* = 0.5*, ωSH* = *ωSE*, and (b) *MSH* = 1× 1.15*, MSE* = 0.8 × 1.15*, ωSH* = *ωSE* .Technically cannot be met by the nine-switch converter. Instead,the nine-switch converter only allows upper dc-rail clampingfor its upper terminals, and lower dc-rail clamping for its lowerterminals, which so far can only be met by the less commonlyadopted 120◦-discontinuous modulation scheme.[2]To formally demonstrate its suitability, relevant offset andmodified reference expressions for the 120◦-discontinuous modulationscheme are derived, and listed in (2), before plotting them in Fig. 4 for illustration of one phase.

Sinusoidal References

$$\begin{cases} V_A = M_{SH}\cos(\omega_{SH}t + \theta_{SH}) \\ V_B = M_{SH}\cos(\omega_{SH}t - 120° + \theta_{SH}) \\ V_C = M_{SH}\cos(\omega_{SH}t + 120° + \theta_{SH}) \end{cases}$$

$$\begin{cases} V_R = M_{SE}\cos(\omega_{SE}t + \theta_{SE}) \\ V_Y = M_{SE}\cos(\omega_{SE}t - 120° + \theta_{SE}) \\ V_W = M_{SE}\cos(\omega_{SE}t + 120° + \theta_{SE}) \end{cases}$$

120^{c}-Discontinuous Modified References

$V_{\gamma}^{1} = V_{\gamma} + V_{SH}, V_{SH} = 1 - max(V_{A}, V_{B}, V_{C}),$

$\gamma = A, B \text{ or } C$

$V_{\partial}^{1} = V_{\partial} + V_{SE}, V_{SE} = -1 - min(V_{R}, V_{Y}, V_{W})$

$\partial = R, Y, \text{or } W$

Using [2], the modulation plots obtained in Fig. 4 clearlyshow the upper reference tied to only the upper dc-rail andlower reference tied to only the lower dc-rail for a continuousduration of 120◦ per fundamental cycle. No crossover ofreferences is observed, implying that the basic modulation rule of-thumb of the nine-switch converter is not breached, and the

120◦-discontinuous scheme is indeed a suitable scheme for reducingits commutation count by 33%. Lower commutationcount would then lead to lower switching losses, whose values depend on the current amplitudes and phases at the two terminals per phase, like all other converters modulated discontinuously.

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B. Series Control Principles

The series terminals of the nine-switch UPQC are given two control functions that can raise the quality of power supplied to the load under normal and sag operating conditions. For the former, the [2] series terminals of the conditioner are tasked to compensate for any harmonic distortions that might have originated at the PCC. where a sizable series voltage needs to be injected to keep the load voltage nearly constant. The overall control block representation realized is shown in Fig. 5, where the subsystem responsible for voltage harmonic compensation is distinctly identified within the rectangular enclosure. As seen, the harmonic compensation subsystem is realized by including multiple resonant regulators in the stationary frame forsingling out those prominent low-order load voltage harmonics,including the 5th, 7th, 11th, and 13th components, for elimination.Transfer functions representing these resonant regulators*Hn*(*s*) and their illustration in the Bode diagram are given in [2][3]and Fig. 6, respectively [2]

$$H_{n}(s) = 2K_{1}\omega_{c}\frac{S + \omega_{C}}{s^{2} + 2\omega_{c}S + \omega_{n}^{2} + \omega_{c}^{2}}$$

C. Shunt Control Principles

As per previous power conditioners, the shunt terminals ofthe nine-switch power conditioner are programmed to compensatefor downstream load current harmonics, reactive power,and to balance its shared dc-link capacitive voltage. where the measured load current is first fed througha high-pass filter in the synchronous frame. The filter blocksfundamental d-axis active component, and passes forward theharmonics and q-axis reactive component for further processing.[2] In parallel, a PI regulator is also added to act on the dc-linkvoltage error, forcing it to zero by generating a small d-axis controlreference for compensating losses, and hence maintainingthe dc-link voltage constant. The sum of outputs from the filterand PI regulator then forms the control reference for the measuredshunt current to track. Upon tracked properly, the sourcecurrent would be sinusoidal, and the load harmonics and reactivepower would be solely taken care of by the proposed powerconditioner.

V .SIMULATION RESULTS AND TABLES

With such flexibility built-in, two distorted cases were programmed with the first having a lower total harmonic distortion (THD) of around 4.18%. This first case, being less severe, represents most modern grids, regulated by grid codes, better. The second case with a higher THD of around 11.43% was included mainly to show that the nine-switch UPQC can still function well in a heavily distorted grid, which might not be common in practice. Equipped with these two test cases, experiments were conducted with the shunt compensation scheme shown always activated, so as to produce the regulated dc-link voltage needed for overall UPQC operation.

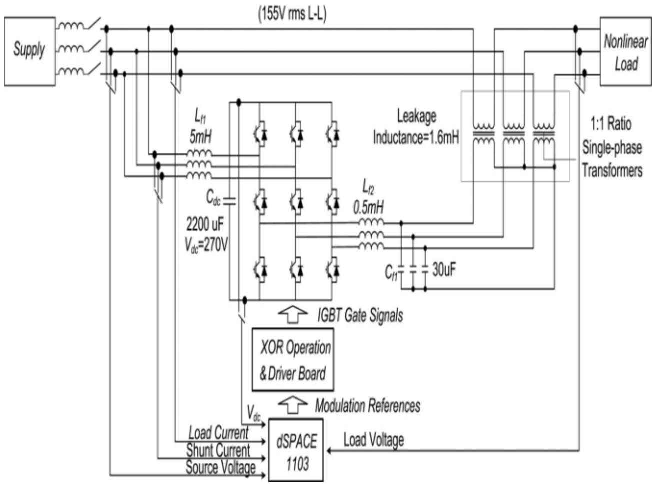

Fig4. Simulation circuit diagram of upqc

TABLE-III: :LOAD VOLTAGE COMPENSATION RESULTS

	5^{th}	7^{th}	11^{th}	13^{th}	5^{th}	7^{th}	11^{th}	13^{th}
No Compensation	2.58%	2.79%	0.85%	1.35%	9.13%	5.59%	3.16%	2.39%
	THD = 4.18%				THD = 11.43%			
With Compensation	0.11%	0.34%	0.06%	0.46%	0.01%	0.39%	0.11%	0.70%
	THD = 0.92%				THD = 1.12%			

on the other hand, was first deactivated, and then activated to produce the two sets of comparative load voltage data tabulated in Table III. The data obviously show that the proposed nine-switch UPQC is effective in smoothing the load voltage, regardless of the extent of low order grid harmonic distortion introduced. To strengthen this observation, Fig. 5 shows the supply, series injection, and load voltages for the second test case with a higher grid THD, and with both series and shunt compensation activated. The supply voltage is indeed distorted, and would appear across the load if series compensation is deactivated and the transformer is bypassed. effectiveness can be found at the bottom of Fig. 5 Roughly, the same results were also obtained when the nine switch converter was replaced by its back-to-back precedence with all other system parameters and control schemes keptunchanged. switching harmonicsproduced, which will not be prominent in those filteredquantities of interest, shown in Table III and Fig. 5. Producingthe same results is however still an advantage for thenine-switch converter, since it achieves that with three lessersemiconductor switches, and hence a lower system cost.

. These waveforms collectively prove that the sag has been blocked from propagating to the load, while yet using lesser semiconductor switches. Complementing, Fig.5 Shows the grid, shunt injection, and load currents during the same normal to sag transition and its recovery. The grid current is obviously sinusoidalthroughout the whole transitional process with an increase in amplitude noted during the period of grid sag. This increasein grid current is transferred to the shunt terinal of the nine switchpower conditioner, whose absorbed (negative of injected)current now has a prominent fundamental component, as alsoreflected by the second row of waveforms plotted in Fig. 5Upon processed by the nine-switch power stage, the incrementalpower associated with the higher shunt current is eventuallyforced out of the series terminal as an injected voltage, neededfor keeping the load voltage and power unchanged.Yet another feature verified through the testing is the dc-linkvoltage needed by the nine-switch power conditioner, whosevalue is always higher than that of the back-to-back conditioner,if series compensation is demanded. This increase can, however,be kept small by adopting the carrier division scheme shown inFig. 3. To confirm that, Fig. 4 shows the conditioner dc-linkvoltage regulated at only 270V throughout the whole sag andrecovery process. This dc-link voltage is merely 8% higher thanthat of the back-to-back case, hence verifying those theoreticalreasoning discussed in Sections II-C and III.

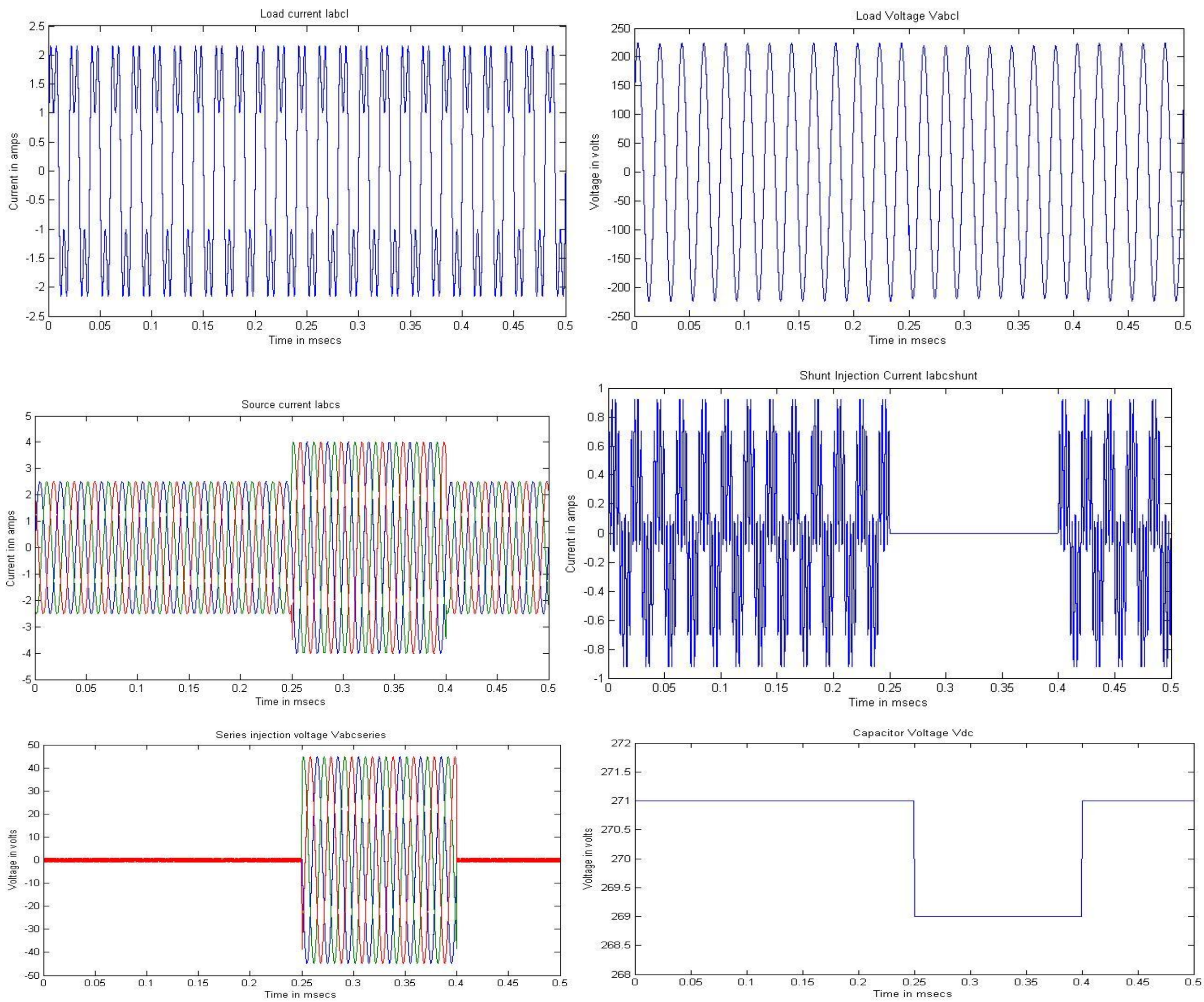

Fig5: simulation results for series injection, and load voltages during normal-sag-normal condition

CONCLUSION

This paper evaluates shortcomings experienced by previousapplications of the newly proposed nine-switch converter. Witha better understanding developed, the conclusion drawn is thatthe nine-switch converter is not an attractive alternative for replacingback-to-back converter with two shunt bridges. Instead,the nine-switch converter is more suitable for replacing backto-back converter in “series–shunt” systems, where one goodexample is the UPQC. As a further performance booster, a modified 120◦-discontinuous modulation scheme is presentedfor reducing the overall commutation count by 33%. Followedup next with proper shunt and series control, harmonics, reactivepower, and voltage sags are compensated promptly with noappreciable degradation in performance. The nine-switch conditioneris therefore proved to be effective, while yet using lessersemiconductor switches. Experimental results for confirmingits anticipated smooth performance have already been obtainedthrough intensive laboratory testing.

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