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RESEARCH ARTICLE

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# VOLTAGE SAG MITIGATION FOR POWER QUALITY ENHANCEMENT USING AN INTEGRATED NINE-SWITCH POWER CONDITIONER WITH FUZZY CONTROLLER

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**ABSTRACT**: A nine-switch power converter 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 reduce the voltage sag and improve the power quality by using a integrated nine switch power conditioner. Aiming further to 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. With an appropriately designed control scheme then incorporated, the nine-switch converter is shown to favourably raise the overall power quality in experiment, 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

## 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]. In addition, they need to be programmed with voltage, current, and/or power regulation schemes 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 back to- back configuration [5], using 12 switches in total and sharing a common dc-link capacitor, as reflected by the configuration drawn in Fig. 1(a).

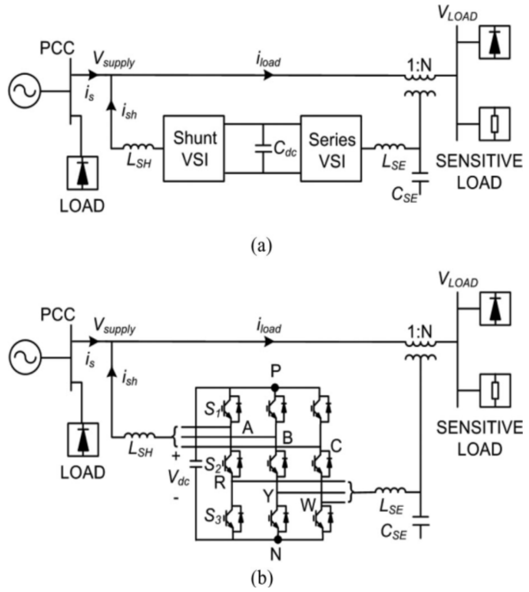


Fig. 1. Representations of (a) back-to-back and (b) nine-switch power conditioner

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 trade off in performance. 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 removing the intermediate electrolytic capacitor for compactness and lifespan extension. Presenting a better reduced semiconductor alternative for high quality series–shunt compensation, this paper proposes a single stage integrated nine-switch power conditioner, whose circuit connection is shown in Fig. 1(b). As its name roughly inferred, the proposed conditioner uses a nine-switch converter with two Sets of output terminals, instead of the usual 12 switch back-to back converter. The nine-switch converter was earlier proposed in [12] and [13] at about the same time, and was recommended for dual motor drives [14], rectifier–inverter systems, and uninterruptible power supplies [15]. More importantly, a much larger dc-link capacitance and voltage need to be maintained, in order to produce the same ac voltage amplitudes as for the back-to-back converter.

Such replacement will limit the full functionalities of the nine-switch converter, as explained in Section II where the nine switch converter is chosen to replace a shunt and a series converter found in an integrated power conditioner, instead of two shunt converters. Underlying operating principles are discussed comprehensively to demonstrate how such “series–shunt” replacement can bring forth the full advantages of the nine-switch converter, while yet avoiding those limitations faced by existing applications.

**SYSTEM DESCRIPTION AND OPERATING PRINCIPLES OF A NINE-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 [18]. Rather than the described, the inverse assignment of functionalities with the shunt converter regulating voltage and series converter regulating current is also possible, as demonstrated in [19]. Being so flexible, the UPQC is 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). Some typical numbers for illustration can be found in [17], 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, which fortunately have already been addressed in [18], 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 shared and no new component can be added. Tradeoffs would certainly surface, meaning that the more reachable goal is to aim for an appreciable reduction in component count, while yet not compromising the overall utilization level by too much. Offering one possible solution then, this paper presents an integrated power conditioner, implemented using the nine-switch converter documented in [12], [13], rather than the traditional back-to-back converter. Before the nine-switch converter can be inserted though, its impact should be thoroughly investigated to verify that there would not be any overburdening of system implementation cost and performance.

B. Nine-Switch Converter Operating Principles and Existing constraints

As illustrated in Fig. 1(b), the nine-switch converter is formed by tying three semiconductor switches per phase, giving a total of nine for all three phases. The nine switches are powered by a common dc link, which can either be a micro source or a capacitor 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 by coordinating the two modulating references per phase, so that the reference for the upper terminal is always placed above that of the lower terminal, as per the two diagrams drawn in Fig. 2. Imposing this basic rule of thumb on reference placement then results in those gating signals drawn in Fig. 2 for the three switches of *S1* , *S2* , and *S3* per phase  Equations for producing them can also be explicitly stated as

$$S_1 = !\, S_1^{\,1} = \begin{cases} ON \text{ if upper reference is larger than carrier} \\ OFF \text{ otherwise} \end{cases}$$

$$S_3 = !\, S_3^{\,1} = \begin{cases} ON \text{ if lower refrence is smaller than carrier} \\ OFF \text{ otherwisse} \end{cases}$$

$$S_2 = S_1^{\,1}$$

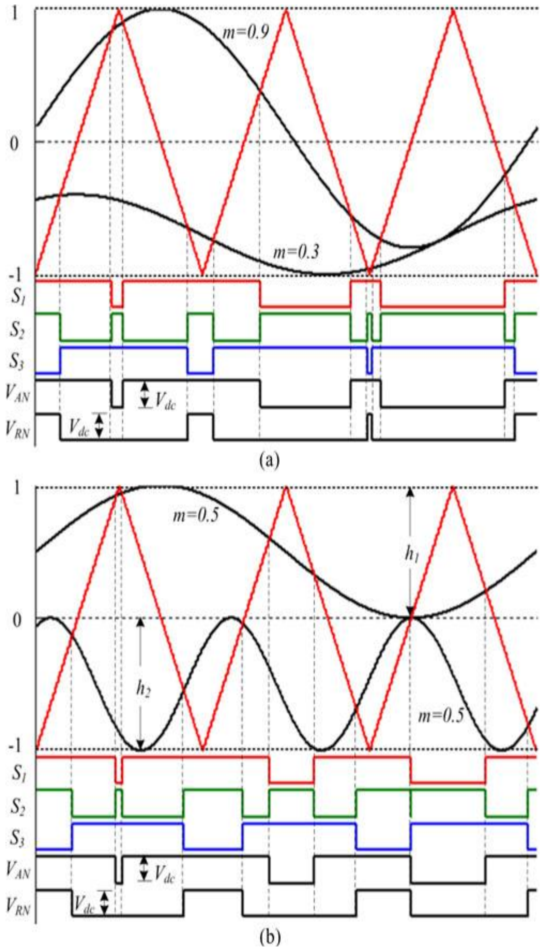


Fig. 2. Arrangements of references having (a) the same frequency but different amplitudes, and (b) different frequencies but the same amplitude.

Where ⊕ is the logical XOR operator. Signals obtained from (1), when applied to the nine-switch converter, then lead to those output voltage transitional diagrams drawn in Fig. 2 for representing *VAN* and *VRN* per phase. Together, these voltage transitions 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 are especially prominent for references having sizable amplitudes and/or different frequencies, as exemplified by the illustrative cases shown in Fig. 2(a) and (b). In particular, Fig. 2(a) shows two references of common frequency limited in their phase displacement, while Fig. 2(b) shows two references of different frequencies limited to a maximum modulation ratio of 0.5 each, extendible by 1.15 times if triplen offset is added, in order to avoid crossover. Considering now the second limitation detailed in Fig. 2(b), a helpful example for explaining it is the nine-switch dual drive system proposed in [13], where references used for modulation can 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.

**C. Proposed Nine-Switch Power Conditioner**

Under normal operating conditions, the output voltage amplitude of the shunt converter is comparatively much larger than the voltage drop introduced by the series converter along the distribution 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 generating gating signals for the three switches per phase would remain 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

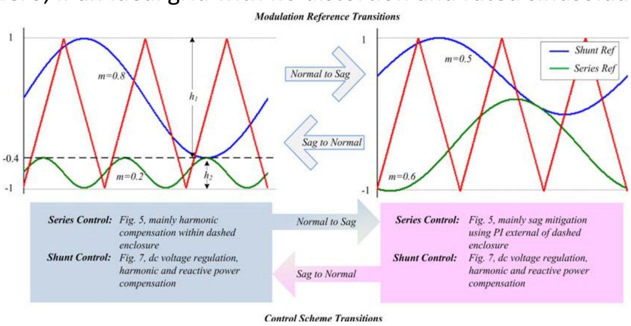


Fig. 3. Transitions of modulating references and control schemes between normal (left) and sag mitigation (right) modes.

In that case, the lowest three switches, labelled as *S*3 for each phase in Fig. 1(b), should always be kept ON to short out the series coupling transformer, and to avoid unnecessary switching losses. If desired, the series transformer can also be bypassed at the grid side to remove unwanted leakage voltage drop without affecting the compensating ability of the shunt converter.

Referring back to the *h*1 and *h*2 carrier band division shown in the left illustration of Fig. 3, it would still need a higher dc-link voltage as a tradeoffs in the UPQC, but the increase is much reduced, and definitely not anywhere close to doubling. Quoting [17] as an example, where a modulation ratio of the series converter can be as low as 0.05 × 1.15 with triplen offset included, the increase in dc-link voltage is merely about 5%, before the same maximum shunt voltage amplitude, like in a back-to-back converter, can be produced by the nine-switch converter. This maximum is however arrived at a reduced maximum modulation ratio of 0.95 × 1.15, instead of 1.15 with triplen offset considered.

Yet another issue to address, before the nine-switch converter can be confirmed as a favourable topology for the "series–shunt" power conditioner, is to study its compensating ability under voltage sag condition. For that purpose, the PCC voltage in Fig. 1(b) is assumed to dip by some amount, which would then subject the higher shunt terminal of the nine-switch converter to a reduced voltage level. In contrast, the lower series terminal must respond immediately by injecting a sizable series voltageat the fundamental frequency ($V_{SERIES} = V_{LOAD} - V_{SUPPLY}$, where $V_{LOAD}$ is the demanded load voltage reference), so as to keep the load voltage close to its Perrault value. Fig. 3 with the same earlier mentioned phase-shift limitation imposed. Fortunately, this limitation will not hinder the operation of the nine-switch conditioner, since large injected series voltage with a demanding phase shift is usually accompanied by a severe sag at the PCC, and hence a much reduced shunt modulating reference. The compressed shunt reference would then free up more carrier space below it for the series reference to vary within, as easily perceived from the example drawn on the right of Fig. 3.

In conclusion, the proposed nine-switch power conditioner can indeed operate well under both normal and sag operating conditions, owing to its auto complementary tuning of shunt and series references within the single common carrier band. Suitability of the nine-switch converter for "series–shunt" replacement is therefore established without any stringent practical limitations encountered, unlike those existing "shunt–shunt" replacements.

**PER UNIT COMPARATIVE DETAILS**

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

For the latter, it is further divided into three subcategories without modifying the context of series– shunt power

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conditioning. The following now describes each of the four cases in detail, before summarizing their features in 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

### *A. Back-To-Back UPQC*

Back-to-back UPQC allows independent control of its shunt and series converters, and hence does not need to divide its carrier band into two, like in Fig. 3. That means $h2$ is zero, and its dc-link voltage can be set to the minimum of $V\text{dc}{-}\text{BB} = 2\sqrt{2}/1.15$ p.u. (subscript BB stands for "back-to-back"), if the nominal RMS grid voltage is chosen as the base. Voltage ratings of the dc-link capacitor, series and shunt switches would thus have to be higher than this value, after adding some safety margin. Current rating of the series switches also has to be higher than $(1 + k)$ p.u., after adding some safety margin, and treating

### *B. Proposed Nine-Switch UPQC*

As shown in Fig. 3, the proposed nine-switch UPQC operates with its carrier band divided into $h1$ and $h2$ . The latter, being much narrower, is for blocking small grid harmonic voltages from propagating to the load, which from the example described in [17], is only about 5% of the full carrier band. The minimum dc-link voltage, and hence voltage ratings of components, must then be chosen based on $V\text{dc-NS} = 1.05\, V\text{dc-BB}$, where Subscript NS is used to represent "nine-switch." Current rating wise, analysis of the nine-switch UPQC is slightly different, because of its merging of functionalities to gain a reduction of three switches. Focusing first at the upper $S1$ switch, maximum current flowing through it would be the sum of shunt $(-k)$ and series $(1 + k)$ currents per phase when $S1$ and $S2$ are turned ON, and hence giving a final value of 1 p.u. Being slightly higher, the common maximum 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 these maximum currents are only for sizing the switches, and should not be exclusively used for computing losses. The reason would be clear after considering $S1$ as an example, where it is noted that the maximum current of 1 p.u. does not always flow. In fact, when $S1$ and $S3$ are turned ON, the current flowing through $S1$ is smaller at $-k$ p.u., whose duration depends on a number of operating parameters like modulation ratio, phase displacement, and others. Analytical computation of losses is therefore nontrivial, as also mentioned in [12], whose simulation approach is now practiced here for computing the UPQC losses. Obtained results for both normal and sag operating modes are subsequently summarized in Table II for easier referencing.

### *C. Nine-Switch UPQC with Only Common Frequency Control*

Nine-switch UPQC, constrained to operate with the same common frequency (CF) at its shunt and series terminals, is not able to compensate for harmonic grid voltages. Parameter $h2$

in Fig. 3 is therefore redundant, and can be set to zero, whose effect is a minimum dc-link voltage that is no different from that of the back-to-back UPQC. The series transformer, being no longer used, can also be bypassed to avoid unnecessary leakage voltage drop, and to divert the large load current away from the UPQC, leaving the three switches per phase to condition only the $-k$ shunt current. Among the switches, the lowest $S3$ switch behaves differently in the sense that it is always turned ON, as explained in Section II-C, and therefore produces only conduction losses. It will only start to commutate when a sag occurs, and the transformer exists its bypassed state. When that happens, 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 calculated loss values.

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

Although not encouraged, the nine-switch UPQC can also be implemented with its carrier band divided into two equal halves, like the different frequency mode studied previously in [12]–[14]. The maximum modulation ratio per reference is then $0.5 \times 1.15$, 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 other series–shunt applications, by simply dividing the carrier band appropriately with $h1$ being much wider than $h2$ , instead of making 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 schemes have their series compensation activated. The same lower losses are also observed with voltage sag mitigation, but not with equal carrier division.The former leads to a smaller dc-link voltage, while the latter causes losses to be smaller, since large load current now does not flow through the nine-switch UPQC. For comparison, values calculated for the back-to-back UPQC operating without series compensation are also included, which clearly show it having slightly lower losses under normal Operating condition. The lower losses here are attributed to the back-to-back UPQC using only six modulated switches for shunt compensation, while the nine-switch UPQC uses six upper modulated switches (*S*1 and *S*2 per phase) and three lower conducting switches (*S*3 ). This finding would reverse when sag occurs, during which the back-to-back UPQC uses 12 modulated Switches, while the nine-switch UPQC uses only nine, and hence producing lower losses.

## MODULATION AND CONTROL

Upon verifying its appropriateness, suitable modulation and control schemes are now presented for controlling the nine switch UPQC with reduced switching losses and roughly the same performance standards as its back-to-back counterpart. Relevant details for attaining these goals are presented shortly in 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 phase references centrally placed within the vertical carrier span. Performance quality obtained would then be comparable to the optimal space vector modulation (SVM) scheme. in Section II-B. Obtaining optimal waveform quality at both terminals of the nine-switch converter is, therefore, not possible, but is not a serious limitation the Fig. 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 clamping for its upper terminals, and lower dc-rail clamping for its lower terminals, which so far can only be met by the less commonly adopted 120◦-discontinuous modulation scheme. To formally demonstrate its suitability, relevant offset and modified reference expressions for the 120◦-discontinuous modulation scheme are derived, and listed in (2), before plotting them in Fig. 4 for illustration of one phase.

Sinusoidal References

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

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

120°-Discontinuous Modified References

$$V_\gamma^1 = V_\gamma + V_{SH}, \quad V_{SH} = 1 - \max(V_A, V_B, V_C),$$

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

$$V_\partial^1 = V_\partial + V_{SE}, \; V_{SE} = -1 - \min(V_R, V_Y, V_W)$$

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

Using (2), the modulation plots obtained in Fig. 4 clearly show the upper reference tied to only the upper dc-rail and lower reference tied to only the lower dc-rail for a continuous duration of 120◦ per fundamental cycle. No crossover of references 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 reducing its commutation count by 33%. Lower commutation count 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.

### *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 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 (_*V*SERIES = _*V*∗ LOAD − _*V*SUPPLY) 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 for singling 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 (3) and Fig. 6, respectively [23]

$$H_n(s) = 2K_1\omega_c \frac{s+\omega_c}{s^2+2\omega_c s+\omega_n^2+\omega_c^2}$$

***C. Shunt Control Principles***

As per previous power conditioners, the shunt terminals of the nine-switch power conditioner are programmed to compensate for downstream load current harmonics, reactive power, and to balance its shared dc-link capacitive voltage. To realize these control objectives, an appropriate control scheme is drawn in Fig. 7, where the measured load current is first fed through a high-pass filter in the synchronous frame. The filter blocks fundamental d-axis active component, and passes forward the harmonics and q-axis reactive component for further processing. In parallel, a PI regulator is also added to act on the dc-link voltage error, forcing it to zero by generating a small d-axis control reference for compensating losses, and hence maintaining the dc-link voltage constant. The sum of outputs from the filter and PI regulator then forms the control reference for the measured shunt current to track. Upon tracked properly, the source current would be sinusoidal, and the load harmonics and reactive power would be solely taken care of by the proposed power conditioner.

**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.

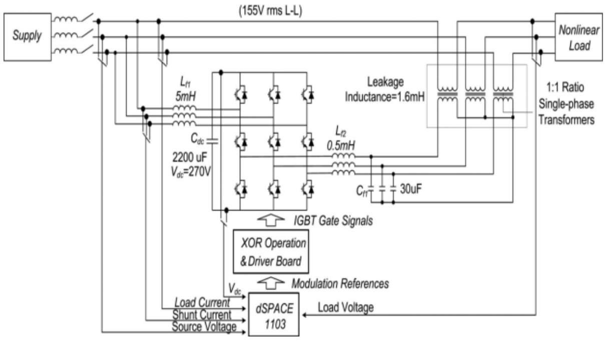
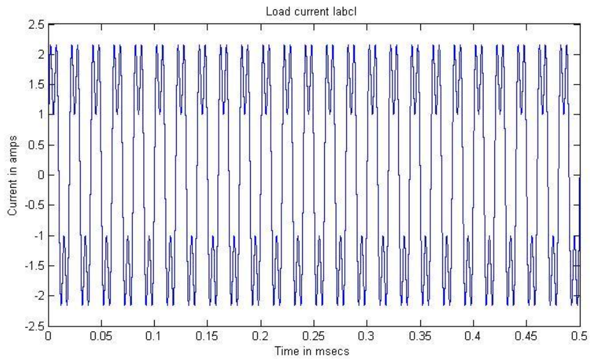
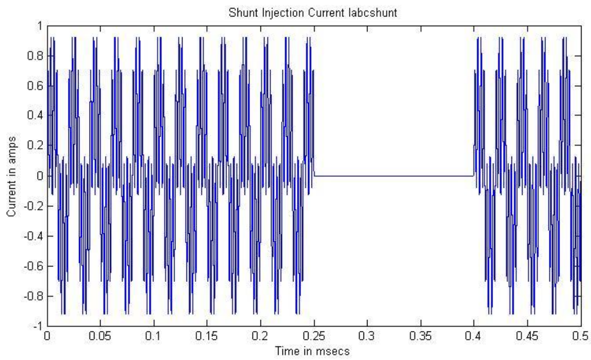
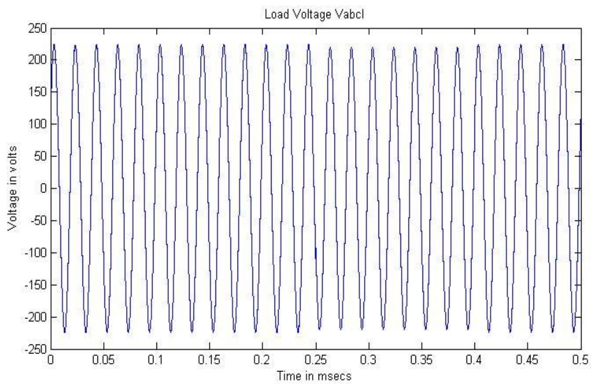



Fig4. Simulation circuit diagram of UPQC



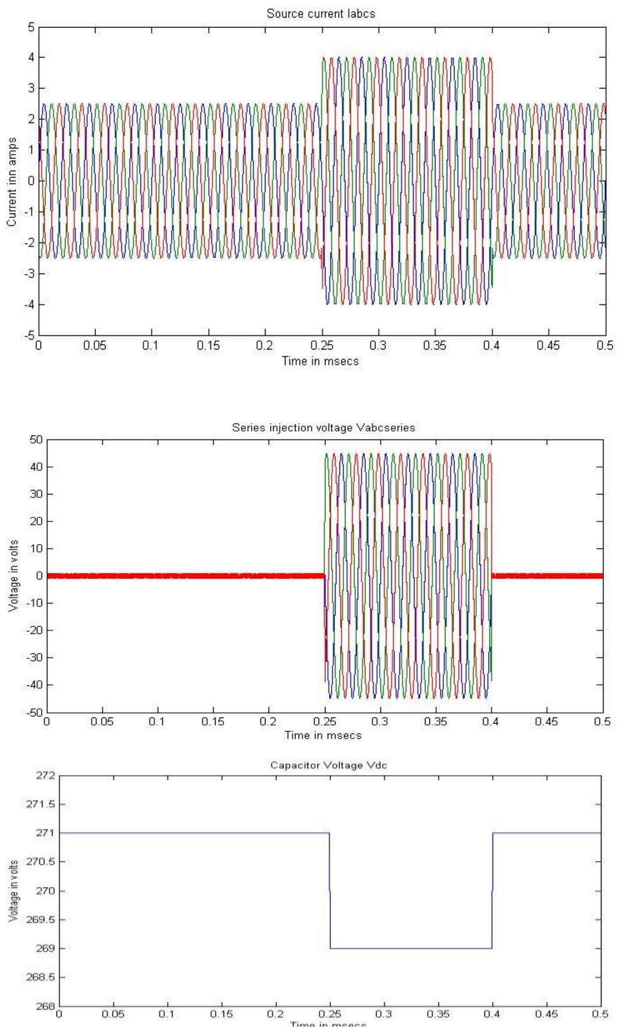



Fig5: simulation results for series injection, and load voltages during normal-sag-normal condition

LOAD VOLTAGE COMPENSATION RESULTS

| | 5th | 7th | 11th | 13th | 5th | 7th | 11th | 13th |
|---|---|---|---|---|---|---|---|---|
| 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 kept unchanged. switching harmonics produced, which will not be prominent in those filtered quantities of interest, shown in Table III and Fig. 5. Producing the same results is however still an advantage for the nine-switch converter, since it achieves that with three lesser semiconductor 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. 12 shows the grid, shunt injection, and load currents during the same normal to sag transition and its recovery. The grid current is obviously sinusoidal throughout the whole transitional process with an increase in

amplitude noted during the period of grid sag. This increase in grid current is transferred to the shunt terminal of the nine switch power conditioner, whose absorbed (negative of injected) current now has a prominent fundamental component, as also reflected by the second row of waveforms plotted in Fig. 12. Upon processed by the nine-switch power stage, the incremental power associated with the higher shunt current is eventually forced out of the series terminal as an injected voltage, needed for keeping the load voltage and power unchanged. Yet another feature verified through the testing is the dc-link voltage needed by the nine-switch power conditioner, whose value 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 in Fig. 3. To confirm that, Fig. 13 shows the conditioner dc-link voltage regulated at only 270V throughout the whole sag and recovery process. This dc-link voltage is merely 8% higher than that of the back-to-back case, hence verifying those theoretical reasoning discussed in Sections II-C and III.

**CONCLUSION**

This paper evaluates shortcomings experienced by previous applications of the newly proposed nine-switch converter. With a better understanding developed, the conclusion drawn is that the nine-switch converter is not an attractive alternative for replacing back-to-back converter with two shunt bridges. Instead, the nine-switch converter is more suitable for replacing back to- back converter in "series–shunt" systems, where one good example is the UPQC. As a further performance booster, a modified 120◦-discontinuous modulation scheme is presented for reducing the overall commutation count by 33%. Followed up next with proper shunt and series control, harmonics, reactive power, and voltage sags are compensated promptly with no appreciable degradation in performance. The nine-switch conditioner is therefore proved to be effective, while yet using lesser semiconductor switches. Experimental results for confirming its anticipated smooth performance have already been obtained through intensive laboratory testing.

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