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Voltage Sag Metigation by Using Integrated Nine Switch Power Conditioners

Mr. Pravin S. Wankhade
M.E. 2nd Year Electrical Engineering, G. H. Raisoni College of Engineering & Management, Amravati, Maharashtra, India
pravinwankhade512@gmail.com

Mr. Chetan M. Bobade
Assistant Professor, G. H. Raisoni College of Engineering & Management, Amravati, Maharashtra, India
chetanbobade@raisoni.net

Abstract- **Modern power system may suffers from many power quality problems like voltage sag, voltage swell, harmonics, flicker, interruption etc, but the voltage sag become major power quality issue and this can causes miss operation of several sensitive load equipment. So to overcome this problem, 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. A nine-switch power conditioner is proposed here that virtually "converts" most of these topological short comings into interesting performance advantages. 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 system then incorporated, the nine-switch converter is best suitable to favorably raise the overall power quality in experiment, hence justifying its role as a power conditioner at a reduced semiconductor cost. In the main thesis MATLAB Model on back to back converter & nine switch converter is formed & compared.**

1. INTRODUCTION

In modern power system reliability and stability are considered to be very important issues. Stability of the system can be achieved by enhancing the power quality. Power quality deals with several issues and problems, maintaining the power quality can be beneficial for both customer and utility. As the system is increasing and is a vast network power quality is main issue to be considered for increasing efficiency, stability and reliability. Power quality may be affected by voltage sag, voltage swell, harmonics, transients, voltage fluctuation, dc offset, interruptions, noise etc.

With an appropriately designed control scheme then incorporated, the nine-switch converter is shown to favourably raise the overall power quality. Static power converter development has grown rapidly with many converter topologies now readily found. Accompanying this development is the equally rapid identification of application areas, where power converters can contribute positively toward raising the overall system quality. In most cases, the identified applications would require the power converters to be connected in series or shunt, depending on the operating scenarios under consideration. In addition, they need to be programmed with voltage, current and 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. For that back to back converter having 12 switches used but to reduce its losses, component count and complexity, an integrated nine switch power conditioner having 6 switches is used.

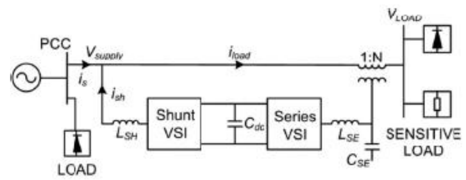


Fig. 1.1 Representation of Back to Back Converter

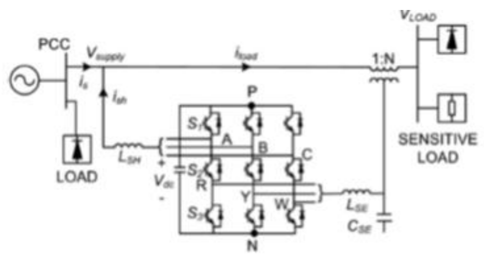


Fig. 1.2 Representation of Integrated Nine Switch Power Conditioners

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, using 12 switches in total and sharing a common dc-link capacitor, as reflected by the configuration drawn in Fig. 1.1. Where available, a micro source can also be inserted to the common dc link, if the intention is to provide for distributed generation in a micro grid without significantly impacting on the long proven proper functioning of the back-to-back configuration.

Presenting a better reduced semiconductor alternative for high quality series–shunt compensation, we have proposed a single stage integrated nine-switch power conditioner, whose circuit connection is shown in Fig. 1.2. 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 and at about the same time, and was recommended for dual motor drives, rectifier–inverter systems, and uninterruptible power supplies. Despite functioning as intended, these applications are burdened by the limited phase shift and strict amplitude sharing enforced between the two terminal sets of the nine-switch converter.

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. Needless to say, the larger dc-link voltage would overstress the semiconductor switches unnecessarily, and might to some extent overshadow the saving of three semiconductor switches made possible by the nine-switch topology. The attractiveness of the nine-switch converter, if indeed any, is therefore not yet fully brought out by those existing applications discussed in. Although follow-up topological extensions can subsequently be found in where a Z-source network and alternative modulation schemes are introduced, they did not fully address those critical limitations faced by the nine-switch converter, and not its traditional back-to-back counterpart.

2. SYSTEM DESCRIPTION AND OPERATING PRINCIPLE OF NINE SWITCH POWER CONDITIONERS

2.1 Back-to-Back Converter Limitations and Recommendation

Fig. 1 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, the inverse assignment of functionalities with the shunt converter regulating voltage and series converter regulating current is also possible, as demonstrated. 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 (_VSUPPLY ≈ _VLOAD). Some typical numbers for illustration can be found in where it is stated that the converter modulation ratio can be as low as 0.05 × 1.15 with triplen 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 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 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. This recommendation is advised as important, since earlier usages of the nine-switch converter for motor drives and rectifier–inverter systems have so far resulted in some serious limitations, which would be brought up for discussion shortly to highlight certain insightful concepts.

2.2. Nine-Switch Converter Operating Principles and Existing Constraints

As illustrated in Fig. 1.2, 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. Like most reduced component topologies, the nine-switch converter faces limitations imposed on its assumable switching states, unlike the fully decoupled back-to-back converter that uses 12 switches.

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

Table 1 Switching States and Output voltage per Phase

Those allowable switching states can conveniently be found in Table I, from which, it is clear that the nine-switch converter can only connect its two output terminals per phase to either Vdc or 0V, or its upper terminal to the upper dc rail P and lower terminal to the lower dc rail N. The last combination of connecting its upper terminal to N and lower terminal to P is not realizable, hence constituting the first limitation faced by the nine-switch converter. That limitation 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. 3.1. Imposing this basic rule of thumb on reference placement then results in those gating signals drawn in Fig. 3.1 for the three switches of S1, S2, and S3 per phase.

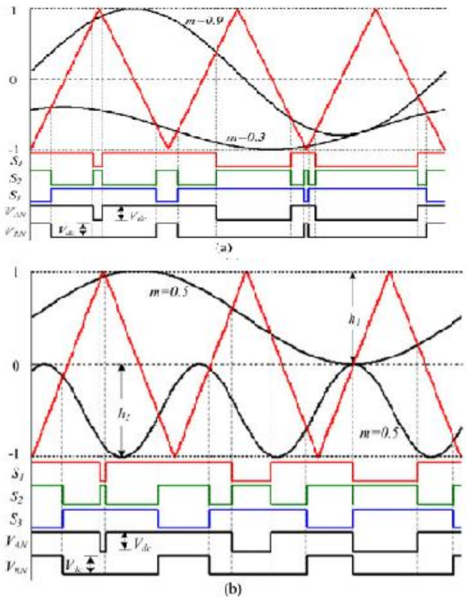


Fig. 2.2.1 Arrangements of references having (a) the same frequency but different amplitudes, and (b) different frequencies but the same amplitude.

Equations for producing them can also be explicitly stated as

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

$$S_3 = !S_3' = \begin{cases} \text{ON}, & \text{if lower reference is smaller than carrier} \\ \text{OFF}, & \text{otherwise} \end{cases}$$

$$S_2 = S_1' \oplus S_3' \qquad (1)$$

Where ⊕ is the logical XOR operator. Signals obtained from (1), when applied to the nine-switch converter and then lead to those output voltage transitional diagrams drawn in Fig. 3.2.1 for representing VAN and VRN per phase. Together, these voltage transitions show that the forbidden state of VAN= 0V and VRN= Vdc 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. 3.2.1(a) and 3.2.1 (b). In particular, Fig. 3.2.1(a) shows two references of common frequency limited in their phase displacement, while Fig. 3.2.1(b) shows two references of different frequencies limited to a maximum modulation ratio of 0.5 each, extendible by 1.15 times if tripled offset is added, in order to avoid crossover. The limited phase-shift constraint, associated with references of the same frequency and combined modulation ratio of greater than 1.15 with tripled offset added (=1.2 in Fig. 3.2.1(a) as an example), has recently been shown to adapt well with online uninterruptible power supplies which indeed is a neat and intelligent application of the nine-switch converter. This, however, is only a single application, which by itself is not enough to bring forward the full potential of the nine-switch converter.

Considering now the second limitation detailed in Fig. 3.2.1(b), a helpful example for explaining it is the nine-switch dual drive system proposed in 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. Such motor operating criteria would force the references to share the common carrier range equally, like that drawn in Fig. 3.2.1(b). The maximum modulation ratio allowed is therefore 0.5 × 1.15 per reference. Even though technically viable, such sharing of carrier is not practically favorable, since to produce the same output voltages, the dc-link voltage maintained, and hence semiconductor stress experienced, must at least be doubled. Doubling of voltage is, however, not needed for the traditional dual converter, whose topological structure is similar to the back-to-back converter, and hence would also support a maximum modulation ratio of unity. Quite clearly then, doubling of dc-link voltage is attributed to the halving of modulation ratios imposed by the nine-switch converter, and is therefore equally experienced by the ac–dc–ac adjustable speed motor drives recommended, where the nine-switch converter is again operating at different frequencies.

Judging from these examples, the general impression formed is that the nine-switch converter is not too attractive, since its semiconductor saving advantage is easily shadowed by tradeoffs, especially for cases of different terminal frequencies. Such unattractiveness is however not universal, but noted here to link only with those existing applications reported to date, where the nine-switch converter is used to replace two shunt-connected converters. References demanded by these shunt converters are usually both sizable, inferring that the carrier band must be shared equally between them, and hence giving rise to those tradeoffs identified earlier. Therefore, instead of "shunt–shunt" replacement, it is recommended here that the nine-switch converter should more appropriately be used for replacing a series and a shunt converter like those found in a power quality conditioner or any other "series–shunt" topological applications. Explanation for justifying that recommendation is provided in Section II-C with all relevant advantages and residual tradeoffs identified.

2.3 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. That indirectly means the modulating reference needed by the shunt converter is much larger than that associated with the series converter, which might simply consist of only the inverse harmonic components for grid voltage compensating purposes. Drawing these details in the carrier range would then result in a much wider vertical range h1 in the left diagram of Fig. 3 for controlling the upper shunt terminal, and a narrower h2 for controlling the lower series terminal (h1_h2). Other operating details like logical equations used for generating gating signals for the three switches per phase would remain unchanged, as per (1).

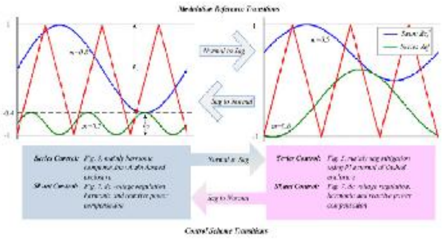


Fig. 2.3 Transitions of modulating references and control schemes between normal (left) and sag mitigation (right) modes.

For h2, a comment raised here is that it can be set to zero, if an ideal grid with no distortion and rated sinusoidal voltage is considered. In that case, the lowest three switches, labeled as S3 for each phase in Fig. 1.2, 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. Tailored operation with an ideal grid is therefore possible, as described, but for modern grids with abundant distributed nonlinear loads, voltage distortion is relatively common, since any amount of harmonic load current flowing through a finite line or transformer impedance would have caused voltage at the PCC to be distorted. Series harmonic compensation of the grid or PCC voltage is therefore technically needed, and hence included here for discussion, if a smoother load voltage is demanded.

3. Experimental Verification And Result

To validate its performance, a nine-switch power conditioner was implemented in the laboratory, and controlled using a dSPACE DS1103 controller card. The dSPACE card was also used for the final acquisition of data from multiple channels simultaneously, while a 4-channel Lecoy digital scope was simply used for the initial debugging and verification of the dSPACE recorded data, but only four channels at a time. The final hardware setup is shown in Fig. 4.1, where parametric values used are also indicated. Other features noted from the figure include the shunt connection of the upper UPQC terminals to the supply side, and the series connection of the lower terminals to the load side through three single-phase transformers. Reversal of terminal connections for the setup, like upper→series and lower→shunt, was also affected, but was observed to produce no significant differences, as anticipated. For flexible testing purposes, the setup was also not directly connected to the grid, but was directed to a programmable ac source, whose purpose was to emulate a controllable grid, where harmonics and sags were conveniently added.

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 always activated, so as to produce the regulated dc-link voltage needed for overall UPQC operation. The series compensation scheme shown previously, 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.

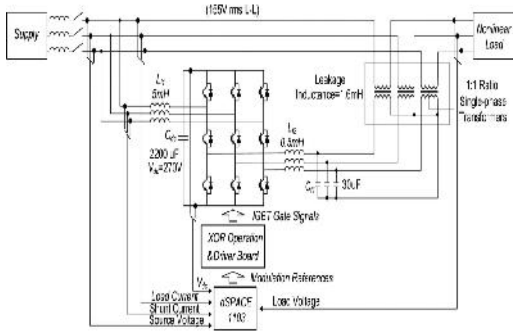
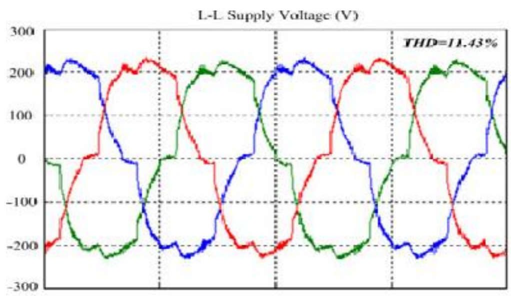


Fig. 4.1 Experimental setup and parameters used for testing



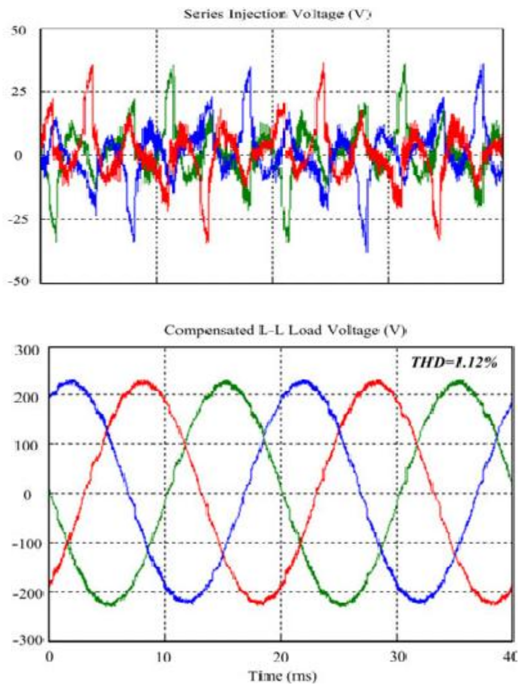


Fig. 4.2 Experimental supply, series injection, and load voltages captured during normal power conditioning mode

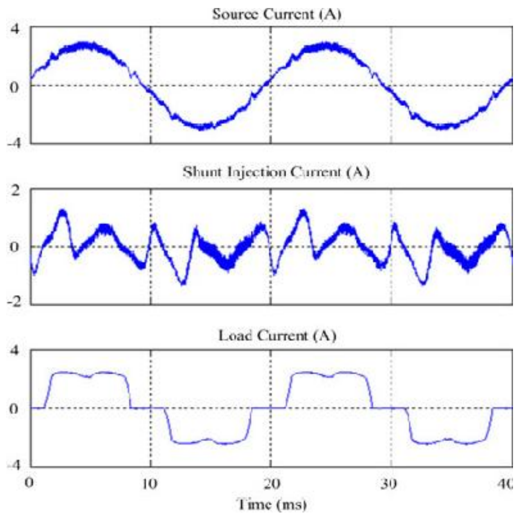


Fig. 4.3 Experimental source, shunt injection, and load currents captured during normal power conditioning mode

To strengthen this observation, Fig. 4.2 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. The distortion would, however, be largely blocked from propagating to the load and upon activating the series compensation scheme with the shunt compensation scheme still kept executing. Example load voltage waveform illustrating this effectiveness can be found at the bottom of Fig. 4.2.

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. This finding is certainly expected, since both converters differ only by their high frequency switching harmonics produced, which will not be prominent in those filtered quantities of interest shown in Table and Fig. 4.2. 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.

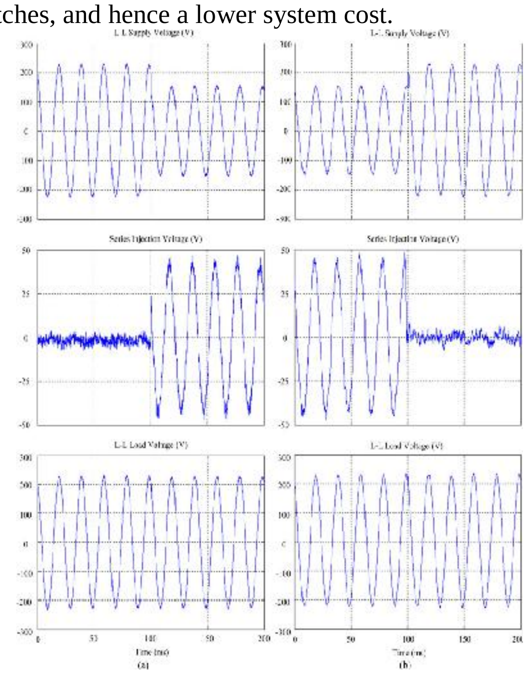


Fig. 4.4 Experimental supply, series injection, and load voltages during (a) normal-to-sag and (b) sag-to-normal transitions

To next verify its shunt compensating ability, Fig. 4.3 shows the source, shunt injection and load currents conditioned by the nine-switch UPQC. Although the load current is heavily distorted, the shunt control scheme is capable of compensating it, so that the grid current drawn is always sinusoidal, as intended.

Fig. 4.5 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. 4.5. 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. 3.3. To confirm that, Fig. 4.6 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.

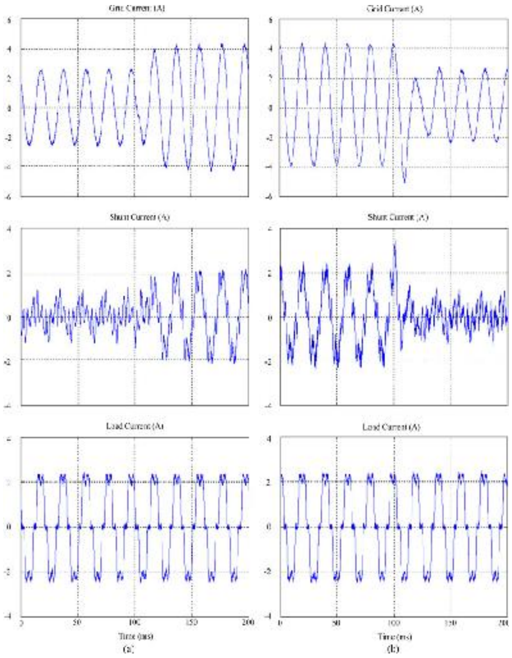


Fig. 4.5 Experimental grid, shunt injection, and load currents during (a) normal-to-sag and (b) sag-to-normal transitions

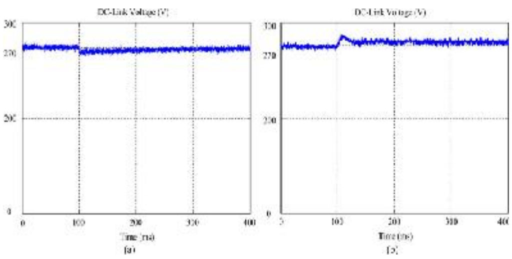


Fig. 4.6 Experimental dc-link voltage during (a) normal-to-sag and (b) sag-to-normal transitions

4. Conclusion

This project 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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