POWER QUALITY ENHANCEMENT IN INDUCTION MOTOR DRIVES BY USING CUSTOM POWER DEVICE

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Original scientific paper

This paper focuses on the advancement of electric power quality tendencies of an induction motor as well as alleviating the consequence on account of the prolonged duration voltage discrepancy and also quite a short time period voltage variance of these kinds of that over voltage, under voltage continuous interruption, impermanent voltage fall together with voltage climb or maybe an entire disappearance of voltage. The proposed alleviating device is a brand new topology of a dynamic voltage restorer (DVR). A DVR is often familiar to alleviating the impact of unusually high voltage variations while making use of a highly effective custom electric power equipment that is to say dynamic voltage restorer. It contains an electric power storage device, filtration systems, voltage source inverters and also injection transformer. There are numerous categories of regulating approaches being employed for mitigation of abnormal voltages. The proposed control approach to DVR will be based upon the 'abc to dqo' conversion methodology employed. The demonstration outcomes can be found in several circumstances of sag, swell and additional harmonic disorder in the supply voltage which exhibits the reimbursement abilities of DVR. The performance of suggested strategy is examined with the aid of computer demonstration through the use of MATLAB/SIMULINK software.

Keywords: *distribution system; dynamic voltage restorer; power quality; unbalanced and distorted load; voltage sags and swells; voltage source inverter*

Poboljšanje kvalitete električne energije u pogonima indukcijskih motora uporabom prilagođenog pogonskog uređaja

Izvorni znanstveni članak

Rad se bavi nastojanjima za poboljšanje kvalitete električne energije indukcijskog motora kao i ublažavanjem posljedica zbog dulje neujednačenosti napona i također kratkog trajanja takvih promjenljivosti napona, stalnih prekida napona, neujednačenog pada i porasta napona ili možda i potpunog nestanka napona. Predloženi uređaj za ublažavanje ovih pojava je sasvim nova topologija dinamičkog obnavljača napona (dynamic voltage restorer (DVR). DVR ublažava djelovanje neuobičajeno velikih promjena napona i koristi visoko učinkovit prilagođen električni uređaj, t.j. dinamički obnavljač napona. Sastoji se od uređaja za akumuliranje električne energije, sustava za filtriranje, pretvarača izvora napona i ispravljača ubrizgavanja. Postoje brojni regulatori za ublažavanje abnormalnih napona. Predloženi pristup DVR-u temeljit će se na primijenjenoj metodologiji konverzije 'abc do dqo'. Primjeri za demonstraciju mogu se naći u nekoliko slučajeva slabljenja, rasta i dodatnog harmonijskog nereda u naponu na kojima se pokazuju mogućnosti DVR-a. Izvršenje predložene strategije ispitano je pomoću demonstracije na računalu uporabom softvera MATLAB/SIMULINK.

Ključne riječi: *dinamički obnavljač napona; kvaliteta električne energije; neuravnoteženo i izobličeno opterećenje; pad i porast napona; pretvarač izvora napona; sustav raspodjele*

1 Introduction

Voltage unpredictability is most frequent power quality (PQ) trouble in industrial distribution systems that influence the induction motor behaviour. The voltage disturbances predominately contain the voltage sags, swells (power, speed, torque and possible stall) harmonics (losses and torque), unbalanced quite short interruptions, transient over voltage and under voltage and flicker [1]. These voltage interruptions inauspiciously effect voltage vulnerable load appliances in automatic production lines, high precision processing, buildings, rolling mills, textile mills. These kinds of voltage and challenging experience interferences resulting in substantial cost-effective and or data losses [3 - 5]. Voltage sags are referred to as reducing of root mean square voltage at power frequency for durations from 0,5 cycles to 1 minute. It is actually therefore possible for the sag of a short-time moment to cause problems in some sensitive equipment [6, 7]. Voltage sags may be caused by switching actions associated with impermanent disconnection of supply, the progression inrush current associated with the commencing of induction motor loads or steady stream of fault currents due to short circuit faults which includes single line to ground fault in a power system (SLG). These kinds of phenomena would probably originate from the customers system or from a public supply network [8, 9]. Voltage swells are brief magnifications in root mean square voltage between 1,1 pu and 1,8 pu at the power frequency amounts of time from 0,5 cycles in 1 minute.

As with sags, swells will most certainly be associated with system incoherent conditions, but they are not as preferred as voltage sags. One way that a swell presents itself from the temporary voltage intensify on the healthy phases through the course of due to the fact SLG fault swells can also be a result of swapping of a limitless demand or perhaps energizing a limitless capacitor bank [10, 11].

The preliminary operation of the DVR is to inject a voltage of the associated magnitude, phase positioning and additional frequency in progression with the distribution feeder to monitor and stay in the desired amplitude and waveform for load voltage even though the voltage is out of balance or distorted [12 - 14]. Numerous extraction as well as mitigation techniques have been unveiled with distinct restraint algorithm in addition to distinct topologies. A basic topology with effortless restraint is introduced in [15] to replenish voltage unbalance. This technique has taken into consideration the precious time inhibition of the manipulated process along with the DVR outcome filtration system limitation. The suggested restraint technique algorithm for getting grid of together with extenuating the voltage interference without precious time inhibition. The load power factor is apparently also significant parameter in choosing the suitable DPWM method to be utilized in the D-STATCOMs. In general, it is indicate that DPWM methods can be applied to D-STATCOMs for high modulation index [16, 17]. The phase bounces provide the sag depths and also phase transformation information and

facts with commencement and even finish circumstances. The powerful reaction of the suggested restraint approach algorithms is examined through the use of the MATLAB software package. After that the outcomes are highlighted to suggest the prospective benefit from the suggested technique for regulating DVR.

2 Dynamic Voltage Restorer (DVR)
2.1 Introduction

Due to the quick variations within the supply voltage, the performance of crucial loads like semiconductor fabrication plants, paper mills, food process plants and automotive assembly plants will be affected. The most frequently manifesting interruptions in the source voltages are the voltage sags or perhaps inflate that are able to be as a result of interruptions occurring in the transmission system, neighbouring feeder imperfections or maybe fuse or perhaps breaker functioning. Voltage sags of perhaps 10 % lowering of magnitude, sustainable for $5 \div 10$ cycles can bring about more expensive deterioration in significant loads. They are able to take place as a consequence of symmetrical or maybe unsymmetrical imperfections. Uncompensated nonlinear loads in the distribution system may cause harmonic elements in the supply voltages. To alleviate the complications brought on by low quality of power supply, series connected compensators are recognized as Dynamic Voltage Restorer (DVR).

An Active Voltage Restorer is a series associated solid state apparatus that injects voltage into the system to be able to adjust the load side voltage. It is typically positioned in a distribution system between the supplies in addition to the significant load feeder. Their most important performance will very quickly recuperate the load-side voltage in the eventuality of an interference to be able to stay clear of any kind of power disturbances to that particular load. There are many different circuit topologies together with managing strategies which they can use to put a DVR into practice.

The DVR has also the capability to handle line voltage harmonics reimbursement, elimination of transients in voltage and also weakness current boundaries. To be able to alleviate voltage sag, DVR really should be competent at generating in addition to consuming active as well as reactive power to and from the grid. To appropriate particular voltage sag, not merely voltage but additionally active or reactive power supplements are essential. The DVR can result in making the reactive power; nevertheless the infused active power should originate an important part of the DVR from the energy storage. Consequently minimization of active power injections is very important to enhance the lift of the energy storage. The most important aspects of the DVR are injection transformer, harmonic filtration system; voltage source converter and also restraint as well as proper protection systems are highlighted in subsequent chapters.

2.2 Injection/booster transformer

The Injection enhancement supplement electrical equipment could be a specifically created electrical device which makes an endeavour to restrict the coupling of noise together with transient energy from the initial

feature to the supplementary element. It connects the DVR to the distribution network through the HV-windings in addition to transformers and also contented couples the injected counterbalancing voltages directed by the voltage supply converters to the inbound supply voltage. Furthermore, the Injection/Booster electrical device provides the intention of uninflected the load from the system.

2.3 Harmonic filter

The most important process of harmonic filtration system will be to continue the harmonic voltage content directed by the inverter within reasonable limits. These kinds of filtration systems are settled at the high voltage side to stay away from introductions in phase position transformation that may interrupt the restraint algorithm.

2.4 Voltage Source Converter (VSC)

A VSC is a power electronics system which includes a storage device together with swapping systems, which can make a sinusoidal voltage at almost any essential frequency, magnitude, and also phase position. In the DVR utilization, the VSC is used as a tool to momentarily upgrade the supply voltage or even generate the portion of the supply voltage that is being neglected. A number of circuit topologies are offered for the VSC however the often used technique is the two levels or multilevel three-phase converter which secures a DC capacitor between almost all phases. The intent behind this capacitor is specifically to consume harmonic ripple in addition to consequently there are a comparatively compact energy storage demand, particularly when in particular when functioning in well-balanced circumstances.

2.5 Switching devices

There are actually four main kinds of switching gadgets: Integrated Gate Commutated Thyristor (IGCT), Insulated Gate Bipolar Transistors (IGBT), Gate Turn- off Thyristor (GTO), and in addition to Metal Oxide Semiconductor Field Effect Transistors (MOSFET). Every version of gadget possesses its own positive aspects as well as restrictions. The IGCT is a contemporary streamlined device with upgraded performance effectiveness and also trustworthiness which allows developing VSC with substantial power ratings. As a consequence of the serious advanced converter layout with IGCTs, the DVR can easily replenish declines that happen to be beyond the capacity of an earlier period DVRs making use of typical appliances.

2.6 Storage devices

The objective is usually to furnish the essential energy to the VSC by means of DC link for the generation of injected voltages. Batteries and even Ultra capacitors are the most typical varieties of energy storage systems. Batteries may be very beneficial in case a very high voltage battery arrangement is employed. Particular ultra-capacitors are able to carry the expense over prolonged amounts of time, to be able to behave like a battery. Nevertheless, in contrast to batteries, these kinds of ultra-

capacitors possess a quick charge precious time together with considerably longer existence. Actually, the capacity of the stored energy establishes instantly the existence of the sag and this can be mitigated by the DVR.

2.7 Control and protection system

The control system of the common arrangement ordinarily is made up of Digital Signal Processing (DSP) boards. The equipment similar to identify and also modification are offered by the software on the DSP board. Filtration systems are typically employed for these kinds of requirements. The most frequent varieties of the filtration system algorithm are the Fourier Transform (FT) as well as the Wavelet Transform.

3 DVR principles of operation

The DVR is custom made electric power equipment which may be associated in series with the distribution system as shown in Fig. 1. The DVR is enforced committed voltage source converter that injects a dynamically manipulated voltage in series to the bus voltage through a booster transformer. The temporary amplitudes of three injected phase voltages brought on by transient distractions in the ac feeder will probably be rewarded by means of the exactly same voltage produced through the converter in addition to be injected on the platform voltage level by way of the booster transformer.
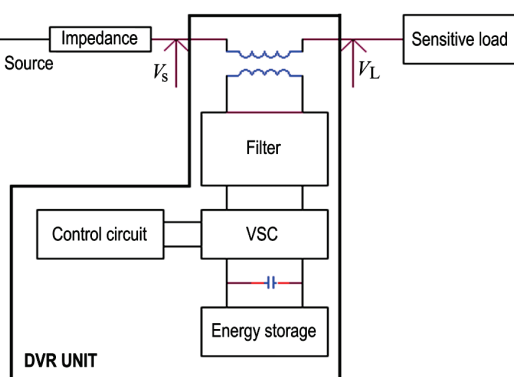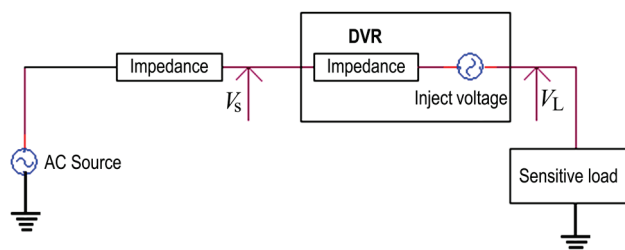

Figure1 DVR Operation

Figure 2 Equivalent circuit of DVR

The DVR performs individually of the sort of problem or perhaps almost any affair that takes place in the system, given that the complete system is still linked with the supply grid, i.e. the line breaker will never trip. For the majority of instances, a much more affordable design can be accomplished by exclusively counterbalancing the positive and negative sequence components and parts of the voltage interference noticed at the input of the DVR. For an ordinary distribution bus

arrangement, as a consequence of unbounded impedance the absolutely zero sequence part of interference is not likely to permeate the step down transformer.

Fig. 2 exhibits the comparable circuit of the DVR, whenever the source voltage goes up or maybe goes down; the DVR injects a series voltage V_{inj} by means of the injection/booster transformer to ensure the preferred load voltage magnitude V_L is generally preserved. The series injected voltage of the DVR may be written as

$$V_{inj} = V_L + V_s ,\qquad(1)$$

in which V_L is the preferred load voltage magnitude, V_s is the source voltage in the course of sags/swells situation. The load current I_L is written by,

$$I_L = \frac{P_L \pm J \cdot Q_L}{V_L}.\qquad(2)$$

4 Principles of vector control

The fundamentals of vector control implementation can be explained with the help of Fig. 3 in which the machine model is represented in a synchronously rotating reference frame. The inverter is not right now there from the figure, given that there is unity current gain that is definitely, it makes current. i_a, i_b and i_c as dictated by the corresponding command current i_a*, i_b* and i_c* from the controller. A machine design with interior conversion rates is demonstrated on the right side of Fig. 3. The machine terminal phase current i_a, i_b and i_c are converted to i_{ds}^s and i_{qs}^s components by $3\varphi/2\varphi$ transformation. These are generally then modified to synchronously revolving structure by unit vector elements $\cos\theta_e$ as well as $\sin\theta_e$ before employ those to the d_e-q_e machine design while presented. The controller can make a couple of phases of inverse modification, as shown, so as to ensure that regulate currents i_{ds}* and also i_{qs}* correspond to the machine currents i_{ds} as well as i_{qs} respectively. Additionally, the unit vector ensures appropriate positioning of i_{ds} with the flux vector ψ_r and i_{qs} perpendicular to it, as shown. The modification together with inverse transformation along with the inverter preferably will not combine any kind of basic characteristics, as well as, the consequence of i_{ds} and i_{qs} is instantaneous.
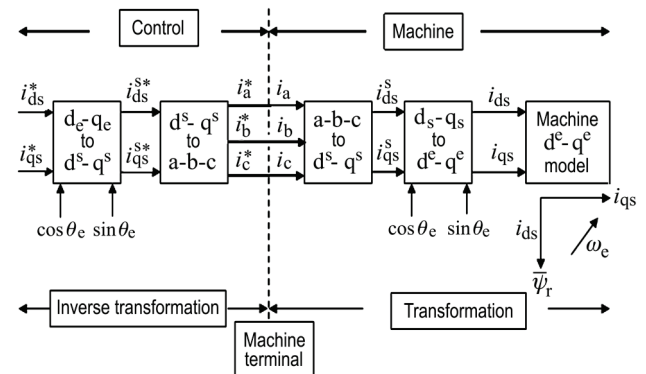

Figure 3 Vector control implementation principle with machine d_e-q_e model

There are essentially two general methods of vector control. One is called direct or feedback method and the other one is indirect or feed forward method. These methods should be mentioned the orientation of i_{ds} with rotor flux Ψ_r, air gap flux Ψ_m, or stator flux Ψ_s is possible in vector management. On the other hand, rotor flux alignment provides natural decoupling control, although air gap or perhaps stator flux positioning can provide a coupling outcome that needs to be rewarded by a decoupling compensation current.

5   Stator flux oriented vector control

The stator flux oriented direct vector control has the advantage that flux vector estimation accuracy is affected by stator resistance R_s variation only. In this section a strategy is developed for stator flux oriented direct vector control by manipulating equations derived from d^e-q^e equivalent circuits.

$$(1 + ST_r)\Psi_{dr} - L_m i_{ds} - T_r \omega_{sl}\Psi_{qr} = 0 \tag{3}$$

$$(1 + ST_r)\Psi_{qr} - L_m i_{ds} - T_r \omega_{sl}\Psi_{dr} = 0 \tag{4}$$

In (3) and (4) Ψ_{dr}, Ψ_{qr} are to be eliminated and replaced by Ψ_{qs} and Ψ_{ds},

$$i_{dr} = \frac{\Psi_{ds}}{L_m} - \frac{L_s}{L_m} i_{ds} \tag{5}$$

$$i_{qr} = \frac{\Psi_{qs}}{L_m} - \frac{L_s}{L_m} i_{qs} \tag{6}$$

$$\Psi_{dr} = \frac{L_r}{L_m}\Psi_{ds} + \left(L_m - \frac{L_r L_s}{L_m}\right) i_{ds} \tag{7}$$

$$\Psi_{qr} = \frac{L_r}{L_m}\Psi_{qs} + \left(L_m - \frac{L_r L_s}{L_m}\right) i_{qs} \tag{8}$$

The relation between stator, rotor fluxes and stator current is obtained by (7) and (8), substituting (7) and (8) in (3) and (4) respectively and multiplying both sides by L_m/L_r.

$$(1 + ST_r)\Psi_{ds} = (1 + \sigma ST_r)L_s i_{ds} \\ - \omega_{sl}T_r[\Psi_{qs} - \sigma L_s i_{qs}] \tag{9}$$

$$(1 + ST_r)\Psi_{qs} = (1 + \sigma ST_r)L_s i_{qs} \\ - \omega_{sl}T_r[\Psi_{ds} - \sigma L_s i_{qs}] \tag{10}$$
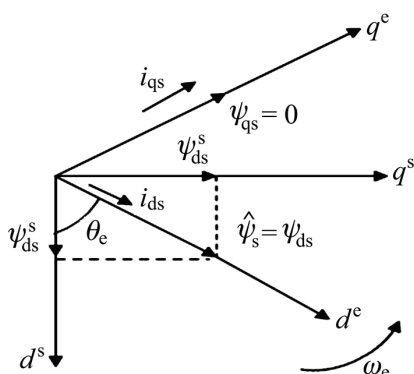

Figure 4 Phasor diagram with stator flux oriented vector control

Fig. 4 shows the stator flux oriented vector control, q_s=0, d_s=$\hat{\Psi}_s$ therefore,

$$(1 + ST_r)\Psi_{ds} = (1 + \sigma ST_r)L_s i_{ds} - [\sigma L_s T_r \omega_{sl} i_{qs}] \tag{11}$$

$$(1 + \sigma ST_r)L_s i_{qs} = \omega_{sl}T_r[\Psi_{ds} - \sigma L_s i_{qs}] \tag{12}$$
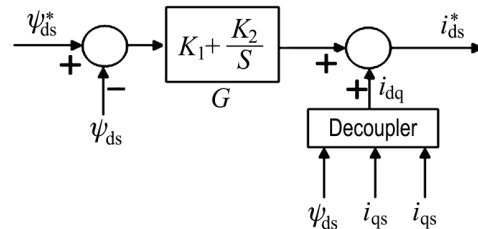

Figure 5 Feed forward decoupling signal injection in stator flux oriented vector control

Fig. 5 shows feed forward decoupling signal injection in stator flux oriented vector control. The decoupling indication i_{dq} becoming inserted the flux restrain loop to make i_{ds}* mainly because a control signal.

$$i_{ds}^* = G(\Psi_{ds}^* - \Psi_{ds}) + i_{dq} \tag{13}$$

where $G = K_1 + K_2/S$,

$$(1 + ST_r)\Psi_{ds} = [(1 + \sigma ST_r).G(\Psi_{ds}^* - \Psi_{ds}) \\ + (1 + \sigma ST_r)i_{dq} - \sigma T_r \omega_{sl} i_{qs}] \tag{14}$$

For decoupling control of Ψ_{ds} with help of i_{dq}, terms, $(1 + \sigma ST_r)i_{dq} - \sigma T_r \omega_{sl} i_{qs} = 0$,

$$i_{dq} = \frac{\sigma T_r \omega_{sl} i_{qs}}{(1 + \sigma ST_r)} \tag{15}$$

Fig. 6 shows the block diagram of stator flux oriented vector control. The stator resistance R_s is a function of stator winding temperature only, it can be easily compensated. The i_{dq} accuracy can be affected by parameter variation, but being within a feedback control loop, this effect can be neglected. The slip signal ω_{sl} can be estimated and then subtracted from the frequency ω_e estimation to estimate the speed signal.
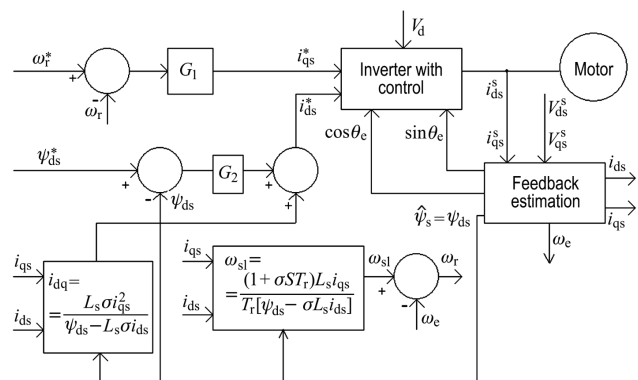

Figure 6 Stator flux oriented vector control

5.1 Voltage vector equation in machine variable

The winding arrangement for a two pole, three phase star connected, and symmetrical induction machine is

shown in Fig. 7. The stator windings are exactly the same, sinusoidal dispersed windings, downgraded by 120 degree with Ns similar turns as well as resistance r_s. The rotor windings will also be considered as three identical sinusoidal distributed windings, displaced by 120 degree with N_r equivalent turns and resistance r_r. The stator magnetic axes coincide with the direction of f_{as}, f_{bs}, f_{cs} as specified by the (18) transformation. The voltage equation in machine variable may be expressed as,

$$V_{abcs} = r_s i_{abcs} + p \tag{16}$$

$$V_{abcr} = r_r i_{abcr} + p\lambda_{abcr} \tag{17}$$

$$(f_{abcs})^T = [f_{as} f_{bs} f_{cs}] \tag{18}$$

$$(f_{abcr})^T = [f_{ar} f_{br} f_{cr}] \tag{19}$$

In the above (16) ÷ (19) s subscript denotes variables and parameters related to the stator circuits, and also the r denotes variables and parameters related with the rotor circuits. Both r_s and r_r are diagonal matrices each with non-zero elements. The flux linkages may be expressed as,

$$\begin{bmatrix} \lambda_{abcs} \\ \lambda_{abcr} \end{bmatrix} = \begin{bmatrix} L_s & L_{sr} \\ (L_{sr})^T & L_r \end{bmatrix} \begin{bmatrix} i_{abcs} \\ i_{abcr} \end{bmatrix} \tag{20}$$

The winding inductances are expressed as,

$$L_s = \begin{bmatrix} L_{ls} + L_{ms} & -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & L_{ls} + L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} & L_{ls} + L_{ms} \end{bmatrix} \tag{21}$$

$$L_r = \begin{bmatrix} L_{lr} + L_{mr} & -\frac{1}{2}L_{mr} & -\frac{1}{2}L_{mr} \\ -\frac{1}{2}L_{mr} & L_{ls} + L_{mr} & -\frac{1}{2}L_{mr} \\ -\frac{1}{2}L_{mr} & -\frac{1}{2}L_{mr} & L_{ls} + L_{mr} \end{bmatrix} \tag{22}$$

In (21) and (22) L_{ls}, L_{ms} are respectively leakage and magnetizing inductances of stator windings; L_{lr} and L_{mr} are for the rotor windings.

$$L_{ms} = \left(\frac{N_s}{2}\right)^2 \frac{\pi\mu_0 rl}{g} \tag{23}$$

$$L_{mr} = \left(\frac{N_r}{2}\right)^2 \frac{\pi\mu_0 rl}{g} \tag{24}$$

$$L_{sr} = \left(\frac{N_s}{2}\right)\left(\frac{N_r}{2}\right)\frac{\pi\mu_0 rl}{g} \tag{25}$$

A majority of induction machines are not equipped with coil-wound rotor windings; instead, the current flow in copper or aluminium bars which are uniformly distributed and which are embedded in a ferromagnetic

material whose all bars are terminated in a common ring at each end of rotor. This type of rotor configuration is referred to as a squirrel-cage rotor. It may at first appear that the mutual inductance between a uniformly distributed rotor winding and sinusoidal distributed stator winding. In most cases uniformly distributed winding is adequately described by its fundamental sinusoidal component and is represented by an equivalent three phase winding. Generally, this representation consists of one equivalent per phase; however, the rotor construction if machines are such that its performance is more accurately described by representing each phase with two equivalent windings connected in parallel. Voltage vector equation of the machine can be expressed in machine variable form; it is convenient to refer all rotor variables to the stator windings by appropriate turns ratio.

$$i'_{abcr} = \frac{N_r}{N_s} i_{abcr} \tag{26}$$

$$v'_{abcr} = \frac{N_r}{N_s} v_{abcr} \tag{27}$$

$$\lambda'_{abcr} = \frac{N_r}{N_s} \lambda_{abcr} \tag{28}$$

The magnetizing and mutual inductances are associated with the same magnetic flux path; therefore L_{ms}, L_{mr}, L_{sr} are related as set forth by (23) ÷ (25). In particular,

$$L_{ms} = \frac{N_s}{N_r} L_{sr} \tag{29}$$

$$L'_{sr} = \frac{N_s}{N_r} L_{sr} \tag{30}$$

$$\begin{bmatrix} \cos\theta_r & \cos\left(\theta_r + \frac{2\pi}{3}\right) & \cos\left(\theta_r - \frac{2\pi}{3}\right) \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\theta_r & \cos\left(\theta_r + \frac{2\pi}{3}\right) \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) & \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\theta_r \end{bmatrix} \tag{31}$$

Also from (23) ÷ (25) L_{mr} may be expressed as,

$$L_{mr} = \left(\frac{N_r}{N_s}\right)^2 L_{ms} \tag{32}$$

$$L'_r = \left(\frac{N_s}{N_r}\right)^2 L_r \tag{33}$$

$$L'_{lr} = \begin{bmatrix} L'_{lr} + L_{ms} & -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & L'_{lr} + L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} & L'_{lr} + L_{ms} \end{bmatrix} \tag{34}$$

$$L'_{lr} = \left(\frac{N_s}{N_r}\right)^2 L_{lr} \tag{35}$$

The flux linkages may be expressed as,

$$\begin{bmatrix} \lambda_{\text{abcs}} \\ \lambda'_{\text{abcs}} \end{bmatrix} = \begin{bmatrix} L_s & L'_{sr} \\ (L'_{sr})^T & L_r \end{bmatrix} \begin{bmatrix} i_{\text{abcs}} \\ i'_{\text{abcr}} \end{bmatrix} \quad (36)$$

The voltage vector equation expressed in terms of machine variable refers to the stator windings and may be expressed as

$$\begin{bmatrix} V_{\text{abcs}} \\ V'_{\text{abcr}} \end{bmatrix} = \begin{bmatrix} r_s + pL_s & pL'_{sr} \\ p(L'_{sr})^T & r'_r + pL'_r \end{bmatrix} \begin{bmatrix} i_{\text{abcs}} \\ i'_{\text{abcr}} \end{bmatrix} \quad (37)$$
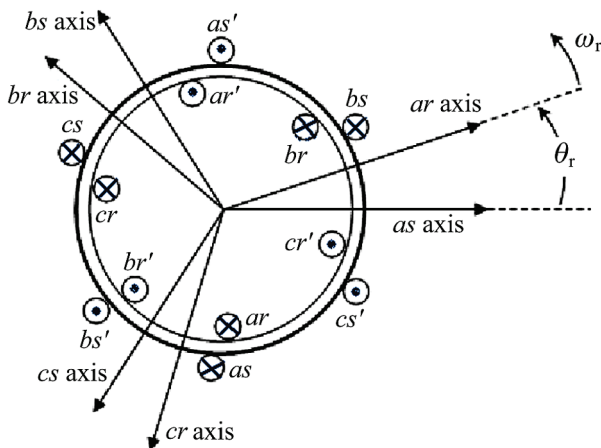

Figure 7 Two pole, 3 phase, star connected symmetrical induction machine

6 Results and discussions

The performance of the proposed DVR techniques and capabilities was investigated with respect to voltage SAG, voltage SWELL, unsymmetrical fault in the point of common coupling, service mains and total harmonic distortion of the system, when the DVR experiences both balanced and unbalanced voltages in distribution line with phase angle jumps. The results are obtained from the system under studying MATLAB/SIMULINK.

6.1 Voltage sag and swell mitigation

Voltage sags are usually associated with system faults but can also be caused by energisation of heavy loads or starting of large power rating of motors. Fig. 8 illustrates the effect of a heavy load or large power rating of motors starting with sag and swell. An induction motor draws 6 to 10 times of its full load current during startup. This will cause a sudden voltage drop but shallow and balanced drop in all three phase voltages. The voltage will then recover slowly as the motor picks up speed. Fig. 8 shows system voltage 'SAG' and 'SWELL' a 50 % voltage initated at 150 ms and it is kept until 200 ms, with total voltage sag duration of 50 ms, and three phase supply voltage magnitudes were increased about 125 % of normal voltage. This operation is carried out in between 300 ms to 400 ms. Fig. 8 shows the voltage injected by the DVR and the compensated voltage sag and swell respectively. As the result of DVR the load voltage is kept at 1pu throughout the simulation including the voltage sag and swell period. Observe that during usual operation, the DVR is doing nothing.
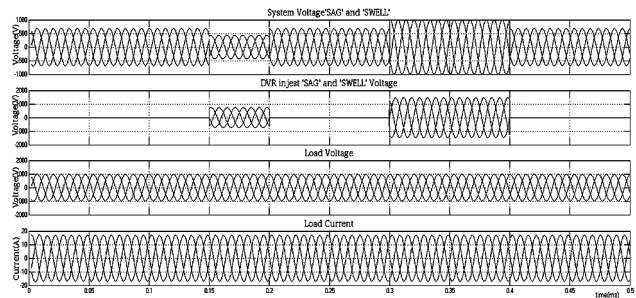

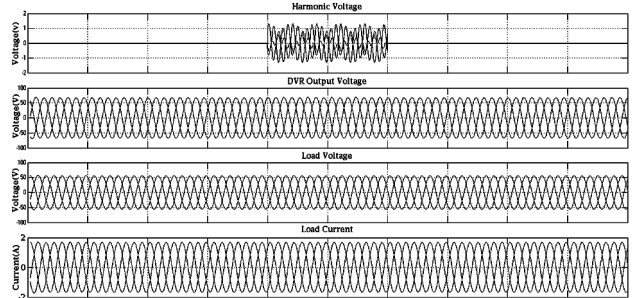Figure 8 Sag and swell occur in system voltage

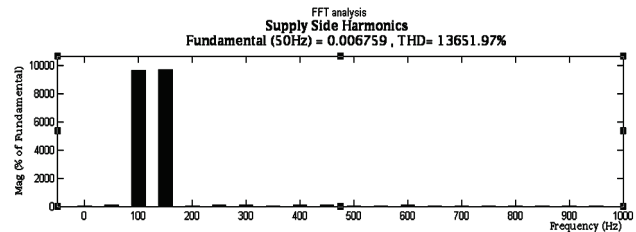Figure 9 Harmonics generated in system
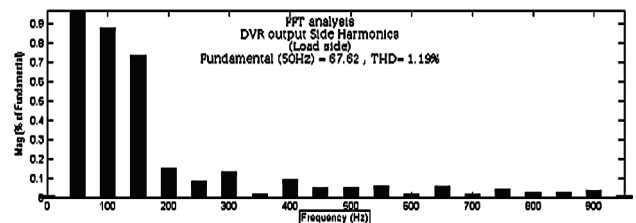

Figure 10 THD in system voltage
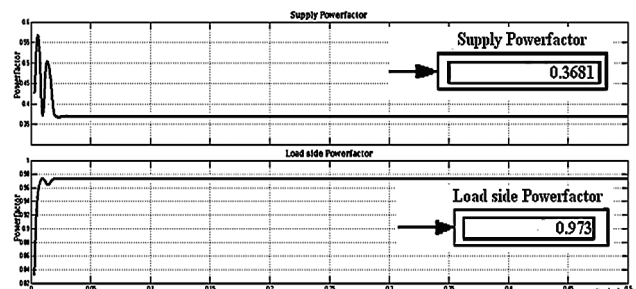

Figure 11 THD in DVR output voltage

Figure 12 Power factor improvement

It quickly injects necessary voltage compensate to smooth the load voltage upon detecting voltage sag and swell. Thus throughout this operation of sag and swell proposed DVR will be ready to compensate both operations effectively with dynamic control strategy. As shown in Fig. 9 the harmonics generation in system voltage is initiated at 200 ms and kept untill 300 ms with total harmonic generation of 100 ms.

The harmonic voltage was injected by the DVR and detained the generated harmonics by filter in DVR. Fig.

10 shows the total harmonic distortion (THD) value of system voltage as 13 651,97 %. Fig. 11 shows the THD value of DVR output voltage as 1,19 % so that the filters in DVR rectify the THD value of system voltage from 13 651,97 % to 1,19 %. Fig. 12 shows the power factor improvement, the supply power factor is 0,3681. The DVR improves the supply power factor from 0,3681 to 0,973 across the load side.

7   Conclusion and future perspective

The main purpose of using DVR in industries is to maximize efficiency in production. This project has proposed an improved progressive phase changing scheme of post-fault voltage. For any fault situation of voltage sag this method is effective, which is proved from the analysis and MATLAB simulation results. The sag transients can be easily mitigated and pre-fault voltage can be established. For real time applications, this may necessitate the application of the microcontroller/ processor with fast speed. The analysis in this paper is done for voltage sag affects single phase and three phase supply. Similarly simulations can be carried for voltage sag, voltage swell, harmonics and three-phase fault. In this paper three-phase fault simulations have not been shown because that is out of scope as far as this project is concerned. Hereby, the effectiveness of proposed method is tested and is proven error free. This proposed method is tested theoretically only however, exact practical testing is left. The effect of harmonics in induction motor and voltage drop due to connection of DVR are to be tested in actual experimental setup. Lab testing of DVR can be implemented as a part of future research work.

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