Published in AJSE, Vol:22, Issue: 1
Received on 23th November 2021
Revised on 2nd March 2023
Accepted on 30th March 2023

AIUB JOURNAL OF SCIENCE AND ENGINEERING
ISSN: 1608 – 3679 (print) 2520 – 4890 (Online)

Performance Comparison of Electric Drives for Chopping/Shredding Sugarcane in Sugar Industry

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***Abstract*— A performance comparison of the conventional slip ring induction motor (SRIM) drive and the recently inducted variable frequency drive (VFD) in the sugar industry, for sugarcane preparation (chopping/ shredding of sugarcane), is carried out to assess their effectiveness and to explore better electric drives for the application. These high inertial machines demand high starting torque and mitigating means to reduce surge load due to the impact load imposed on them. Though, both the drives meet the requirement but the SRIM drives are subjected to huge slip power loss, low power factor, unequal load sharing problem for coupled motors and high drop in rpm, whereas VFDs are subjected to the problems of input current harmonics, high dV/dt stress and common-mode voltage (CMV). In this paper, along with the performance comparison a three/four-level multilevel inverter (MLI) fed open-end winding induction motor (OEWIM) drive is also proposed as an improvement over the existing ones.**

Keywords: Slip resistance, variable frequency drive, multilevel inverter, open-end winding induction motor.

I. Introduction

SUGARCANE preparation is one of the most important processes during sugar manufacturing and consumes around 25-30% of the total power consumption in a sugar factory. The machines for sugarcane preparation are a kicker (optional) followed by 1st cutter (or chopper), 2nd cutter (or leveler) and a shredder. These sugarcane preparatory devices make the sugarcane into fibrous material so that the preparatory index (PI, the degree of fineness or percent of open cells) becomes 85-90% before going to mills for extraction of juice. Such machines, with huge inertia, demand a high starting torque. Conventionally, SRIMs are used as a prime mover in such applications in the sugar industry. For mitigating the surges in the motor load current, some part, typically corresponding to 15% slip at full load, of the starting resistance in the rotor circuit, known as slip resistance, is kept inline throughout the operation [1][2]. For a medium and large capacity factories two mechanically coupled SRIMs are used. One such arrangement, showing twin coupled motor for shredder is shown in Fig. 1(a). This conventional set-up results in inefficient use of the motors due to huge power loss (around 8-12% of the total power consumed) in the slip resistance, poor rpm regulation, low power factor and unequal load sharing.

Of late, in a few factories in India, basic two-level inverter based VFD run squirrel cage induction motors (SCIMs) are installed to overcome the problems associated with the conventional system. The setup is shown in Fig. 1(b). But, such drives are subjected to the problems of input current harmonics, high dV/dt stress and CMV.

In the present study a performance comparison of cane preparation machines, the age-old SRIM based electric drives, the recently inducted two-level inverter based VFDs run SCIMs and the proposed three and four-level MLI based OEWIM drive for the application is presented based on the data collected from various sugar factories and simulation. The simulations are carried out on MATLAB/Simulink. Some relevant data as obtained using Fluke-345 power quality clamp meter

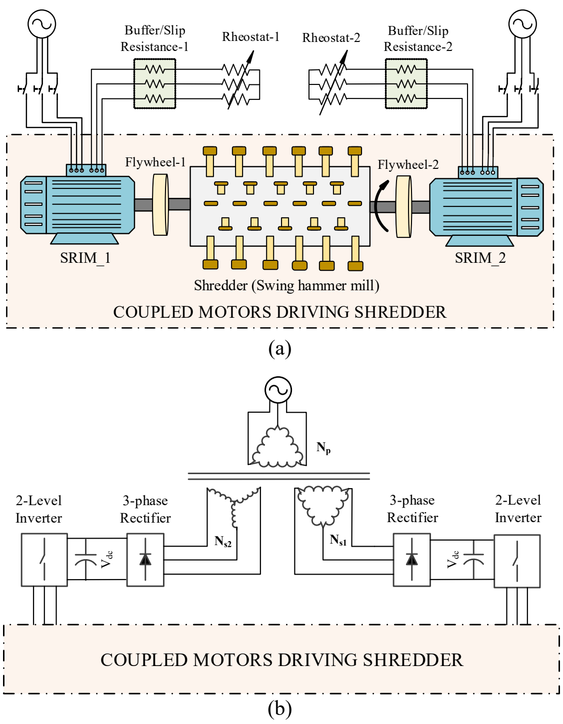

Fig. 1. Existing two types of electric drives for sugarcane preparation (a) SRIM drive. (b) 2-level inverter based VFD.

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during the visits of various sugar factories located in north India are also presented as a part of the study. The rating of motors for sugarcane preparation machines at various factories visited for the data collection were in the range of 200kW to 1000kW. In the present study, for the simulation, two mechanically coupled induction motors of 500kW (415V, 3-ph, 50Hz) each are taken. In the simulation, the various parameters in respect of the motors are obtained from [3]–[5].

II. Discrete Model of the Coupled Induction Motors

Modeling and simulation of the three-phase induction machine is well documented in the literature [6]. Discrete-state model is more suitable for the study of inverter-fed induction motor control [7]. The discrete state model for an induction motor can be extended for the SRIM and OEWIM also. The discrete model of the coupled induction motors (SRIMs, SCIMs and OEWIMs) is implemented in stationary reference frame as defined in [6] and is given by (1)-(6).

The stator and rotor voltage of motor-1 are described by (1a) and (1b) and that for motor-2 is described by (2a) and (2b) respectively.

$$V_{s1}(t) = R_{s1}i_{s1}(t) + \rho L_{s1}i_{s1}(t) \tag{1a}$$

$$0 = R_{r1}i_{r1}(t) + \rho L_{r1}i_{r1}(t) - j\omega\psi_{r1}(t) \tag{1b}$$

$$V_{s2}(t) = R_{s2}i_{s2}(t) + \rho L_{s2}i_{s2}(t) \tag{2a}$$

$$0 = R_{r2}i_{r2}(t) + \rho L_{r2}i_{r2}(t) - j\omega\psi_{r2}(t) \tag{2b}$$

Stator flux and rotor flux in terms of stator and rotor currents are given by (3a) and (3b) for motor-1 and (4a) and (4b) for motor-2.

$$\psi_{s1}(t) = L_{s1}i_{s1}(t) + L_{m1}i_{r1}(t) \tag{3a}$$

$$\psi_{r1}(t) = L_{r1}i_{r1}(t) + L_{m1}i_{s1}(t) \tag{3b}$$

$$\psi_{s2}(t) = L_{s2}i_{s2}(t) + L_{m2}i_{r2}(t) \tag{4a}$$

$$\psi_{r2}(t) = L_{r2}i_{r2}(t) + L_{m2}i_{s2}(t) \tag{4b}$$

Equation (5a) and (5b) gives the torque equations for motor-1 and motor-2, respectively, by considering ψ_{s1}, ψ_{s2} and i_{s1}, i_{s2} as state variables. The total torque produced is given by (6).

$$T_1(t) = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\overrightarrow{\psi_{s1}(t)} \times \overrightarrow{\iota_{r1}(t)}\right) \tag{5a}$$

$$T_2(t) = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\overrightarrow{\psi_{s2}(t)} \times \overrightarrow{\iota_{r2}(t)}\right) \tag{5b}$$

$$T_{total}(t) = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left\{\left(\overrightarrow{\psi_{s1}(t)} \times \overrightarrow{\iota_{r1}(t)}\right) + \left(\overrightarrow{\psi_{s2}(t)} \times \overrightarrow{\iota_{r2}(t)}\right)\right\} \tag{6}$$

In (1)-(6) , R_{s1}, R_{s2} are the stator resistance; R_{r1}, R_{r2} are the rotor resistance; 'ρ' is derivative (d/dt); '*P'* is the number of poles; L_{s1}, L_{s2} are the stator inductance; L_{r1}, L_{r2} are the rotor inductance; L_{m1}, L_{m2} are the mutual inductance; $\psi_{s1}(t)$, $\psi_{s2}(t)$ are stator flux linkages at time '*t'*, $\psi_{r1}(t)$, $\psi_{r2}(t)$ are rotor flux linkages at time '*t*'; $i_{s1}(t)$, $i_{s2}(t)$ are stator current at time '*t'*; $i_{r1}(t)$, $i_{r2}(t)$ are rotor current at time '*t*'; $V_{s1}(t)$, $V_{s2}(t)$, are stator voltage at time '*t'* and $T_1(t)$, $T_2(t)$ are the electromagnetic torque at time '*t'*, correspondingly for the motor-1 and motor-2.

III. Performance Comparison of the Existing Electric Drives

Historically, due to the demand for higher PI of sugarcane, the shredder motor ratings had increased gradually which began to impact negatively on the power houses of the sugar mills and had the potential to result in loss of synchronism of the turbo-alternators (in co-generation section) and factory blackouts. In such isolated power systems for the issue of voltage oscillatory instability, one of the suggested solutions is through AVR compensation [8]. The accepted solution, at that time, for sugar engineers was to keep a slip resistance in the rotor circuit of the SRIMs in line throughout the operation to relieve the stress on the power supply due to large load swings [9][10].

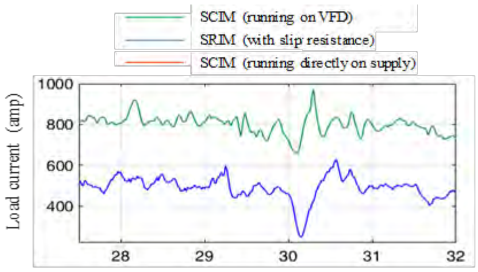
The newly inducted two-level inverter-based VFD fed SCIM system addressed the problems, such as issues of load balancing, huge slip power loss and lowering of the rpm of the motor during peak load conditions, etc. associated with the conventional system. In the factories where the generated voltage level from the alternator (co-generation) itself is 415V, then the VFDs are connected directly to the bus or through a phase shift transformer as shown in Fig. 1(b) and in the factories where the generation voltage level is 11kV then the use of phase shift transformer becomes mandatory. In the present study, a phase shift transformer is used and 415V, 50Hz as input supply to it is taken. The turn ratio for the different windings is given by (7) and the dc-link voltage for each of the VFD is V_{dc}.

$$N_p : N_{s1} : N_{s2} = 1 : 1 : 1/\sqrt{3} \tag{7}$$

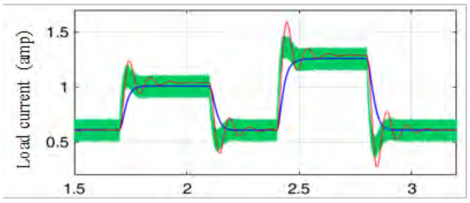
This kind of phase shift transformer results in a 12-pulse rectifier effect at primary while using two single 6-pulse rectifier based VFDs with a 30° phase shift voltage waveform from the star-connected winding (secondary-2) with respect to the delta connected primary and secondary-1 winding.

A. Characteristics of Load Current

The load imposed on these chopping/shredding machines by the pile of sugarcane comes under the category of continuous variable and impact type load [11]. Fig. 2(a) shows the load current (rms) waveforms of chopper (run by SRIM with slip resistance) and shredder (VFD run SCIM) as obtained from the



(a)



(b)

Fig. 2. (a) Load current (rms) for shredder and chopper obtained from the DCS. (b) Simulation results for load current during impact loads.

Distributed Control System (DCS) of M/s Dhampur Sugar Mills (DSM) Ltd., Rajpura, India. The simulation results for stator current for the step (impact) load of 100% and 125% of full load for SCIM (running on VFD), SRIM (with slip resistance) and SCIM (running directly on supply) are shown in Fig. 2(b). The fluctuation in the current as being seen in the figures, which is usual, is due to the uneven feeding of the pile of sugarcane to these machines. It is assumed, as usually happens in the sugar industry, that the motor runs on 60% load during the normal operation. From the figures, it can be seen that the introduction of slip resistance in the rotor circuit does help in the mitigation of swing in load current and thereby the current changes smoothly from one step to the next higher step. However, a huge amount of power is lost in the form of heat in the slip resistance [12]. It can further be seen from the figures that the recently inducted VFD based SCIM system is also able to make the smooth transition of load current for impact load. Therefore, both the existing drives are good at mitigating the surges in load current.

B. Power loss in the Rotor Circuit

The modified rotor equivalent circuit after including the slip resistance, R_{slip}, for the SRIM at the sugarcane preparation machine is shown in Fig. 3. The modified impedance of the rotor circuit is given by (8) and the modified power equation for the rotor circuit is given by (9).

$$Z_{eq}(modified) = X_2 + (R_2 + R_{slip}) + (R_2 + R_{slip})(1-S)/S \quad (8)$$

$$P_{in}(modified) = I^2(R_2 + R_{slip})(1-S)/S + I^2(R_2 + R_{slip}) \quad (9)$$

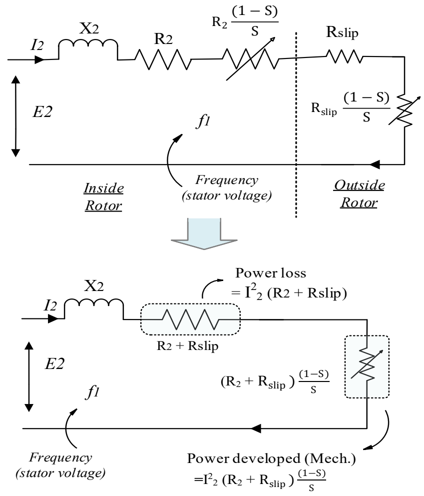
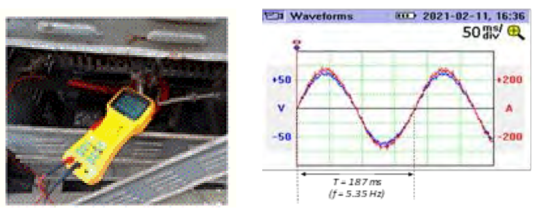


Fig. 3. Modified rotor equivalent circuit of SRIM with slip resistance and various power components

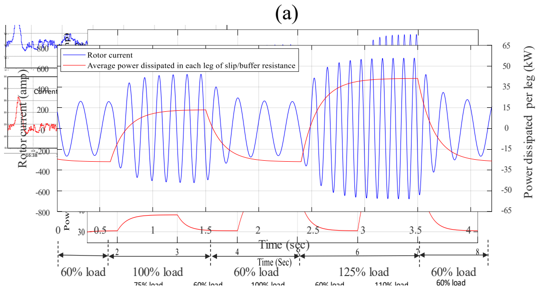
Since for such applications, R_{slip}: $R_2 \approx$ 14:1, therefore, theoretically, around 14% of total input electrical power to the rotor is lost in the slip resistance. Practically, the percentage comes to 8-12% as some part of the power is lost in long cables, which are 10 to 30 meters in length depending upon the installation constraints, connecting the rotor winding to the external slip resistance. One such waveform for the current through and the voltage across one leg of star-connected slip resistance as obtained using Fluke-345 power quality clamp meter from the chopper motor running at around 60% load of a sugar factory named M/s Awadh Sugars Ltd., Seohara India is shown in Fig. 4(a). It can be easily seen that the frequency for the rotor current is about 5.35 Hz making slip 'S', which is given by (10), to be 10.7%.

$$S = f_2/f_1 = 5.35/50 = 0.107 \quad (10)$$

where, 'f_2' and 'f_1' are rotor and stator voltage frequencies, respectively. Therefore, in this particular



(a)



(b)

Fig. 4. (a) Voltage and current for one leg of slip resistance. (b) Simulation results for rotor current and average power loss (per phase)

case, around 10.7% of total input power is lost in the rotor circuit, out of which a major share is in the slip resistance. The simulation result for the rotor current and average power (per phase) dissipation in the slip resistance for various load conditions is shown in Fig. 4(b).The average power loss obtained through simulation conforms with the actual loss measured. Since SCIMs are used in the recently inducted VFD based drives for cane preparatory machines, there is no question of connecting external resistance like in SRIMs and hence there is no issue related to the power loss in slip resistance. As the slip% at full load for such large motors remains in the range of 1-2%, therefore, only a meager (1-2%) slip power loss takes place in the rotor which is usual and inevitable.

C. Load sharing of the Coupled Motors

In the conventional system, preference is given for installing SRIMs of the same make and rating. But in the case of old factories, the motor parameters are rarely found to be identical in these two coupled motors because of rewinding, change in make, repair job, etc. [13][14]. The operating torque of the motor having higher rotor resistance becomes lower than that of the other motor having lower rotor resistance. This shifting of the operating point on the torque-speed graph results in one motor running in an overload condition, while the other motor is not yet fully loaded [15][16]. One such example of unequal sharing of load by two coupled SRIMs (of the same rating) of chopper machine as obtained from the DCS of a sugar factory named M/s DSM Ltd., Rajpura, India is shown in Fig. 5.

In the VFD based drives, the issues related to the unequal load sharing can be addressed in several ways such as by natural load balancing due to slip of the motor or by using scalar control with slip and torque compensations to form the appropriate characteristics by using one motor as the master, which creates a reference on the torque of the motor which is considered to be a slave for the system. Fig. 5 also shows one such case through the trends of the load current of two-level inverter based VFD driven coupled SCIMs with almost equal load sharing. Therefore, this feature is improved in the VFD fed motors in comparison to the conventional ones.

Fig. 5. Load current(rms) by coupled SRIM drive and VFD of a sugar factory obtained from DCS.

D. Effect on RPM and Stopping Time of the Motors

While during impact loads, the slip resistance helps in mitigating the swing in the load current, but, at the same time, the rpm of the motor drops in the same proportion of the increase in the load resulting in the motor operating in the lower range of rpm than it is desired. The drop in rpm may reach up to 15% of the synchronous speed at 100% load condition [17]. At lower rpm not only does the PI reduces but also its consistency is compromised. The recommended tip speed for the shredder is about 100m/s and that of cutters is 60m/s [18]. Keeping in view the governing equations for speed of the motor and the speed requirements for chopper and shredder, the generally accepted synchronous rpm for shredder is 1000 or 750 rpm and for cutters, it is 600 rpm. This limits the fine-tuning of rpm to the nearest best value which could give better results in terms of preparation and power saving. The induction of two-level inverter based VFD run SCIM for cane preparation application addresses this issue including the reduction in the huge dip of rpm during the surge loads. Therefore, for this aspect also, the recently inducted two-level based VFDs proved better in comparison to the conventional one.

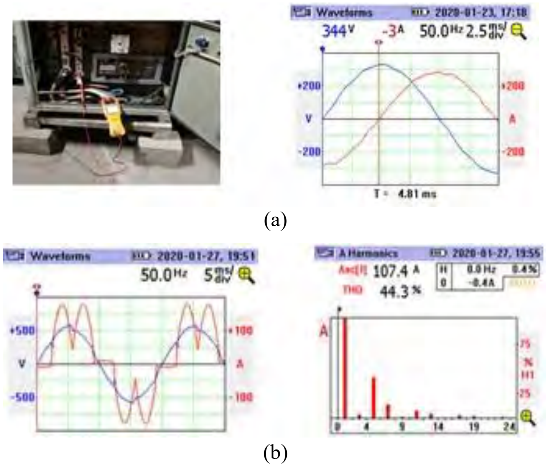
Sometimes, in case of breaking of any hammer while its operation, the shredder motor is required to go for an emergency stop to avoid any further damage to the machine. In such cases, it takes 20-30 min time to completely stop the motor because of its huge inertia. Such delay in stopping the motor not only affects the life of bearings as vibration may develop due to disturbed balancing but also increase the downtime of the process which may cost dearly to the miller. This is one of the demerits in conventional drives. In the case of newly inducted VFD based drives the stopping time, in case of emergency, is reduced drastically. Further, the kinetic energy can also be recovered if regenerative braking is implemented [19][20].

E. Power Factor and Harmonics

The load at sugarcane preparation machines keeps on fluctuating up to +35% and -70% of the rated current of motors making the average current drawn to be too low than the rated current of the motor. Such underutilization of motor capacity makes the motor run at a very low power factor. Owing to the impact loads and the other limitations imposed by the nature of the load, the rating of the motor is recommended to be kept as 33% more than the average power required for the application [10]. Since the motor runs in underload condition during most of the time of its operation the power factor remains poor. Having a lower power factor in induction motor means consuming more reactive current than active current thus creating huge power quality problems in grid systems [21]. One such example of poor power factor as obtained using a power quality meter at a sugar factory named M/s DSCL, Hariawan, India is shown in Fig. 6(a). It can be seen that the phase difference between voltage (phase) and current (line) is 4.81ms. Therefore, the phase current lags behind the phase voltage by (4.81-1.67)ms or 86.58°–30° = 56.58°and hence the power factor comes to be Cos(56.58) = 0.55 lagging.

One of the advantages of using VFD based drives is the improvement in power factor. When a motor is operated by a VFD the displacement between the fundamental voltage and current is not reflected back to the input side of VFD due to the rectification. Diode and IGBT based rectification keeps the drive input current in phase with the supply voltage under all load conditions. Therefore, the power factor remains near unity (approximately 0.98) with VFD [22]. But, one of the main disadvantages of VFDs is the injection of harmonics. The effects of harmonics can include overheating of transformers, cables, motors, generators and capacitors connected to the same power supply with the devices generating the harmonics, computers may fail, circuit breakers may trip and metering may give false readings [23]. For a 415V generating system, installation of phase shift transformer becomes optional and in many cases, to save capital cost, the installation is avoided. In such cases, the two VFDs use individual 6-pulse rectifier circuit because of its simple and low cost structure. This leads to the injection of harmonics in the input current. Fig. 6(b) shows input current waveform and harmonics for a 6-pulse rectifier based VFD connected directly to the bus (without the phase shift transformer) as obtained using a power quality meter at a sugar factory named M/s Wave Industries, Bareilly, Uttar Pradesh (India). The simulation results for input current and inverter output voltage waveform if the VFDs are connected through a phase shift transformer which results in a 12-pulse type arrangement is shown in Fig. 9a.

As the implementation of VFDs is newly inducted in the industry, its further advantages and shortcomings are yet to be seen in the coming future. Apart from the harmonics, the main problems reported to have been with such two-level inverter based VFD run motors in other industries is increase in insulation failures usually caused by turn-to-turn shortening or phase-to-ground faults due to the insulation dielectric breakdown between adjacent turns and CMV making the current flow taking a path through various inherent parasitic capacitances in the motor [23]–[25]. The increased cable length between the VFD and the motor worsens the situation [26]. The same problems are expected to be seen in the near future in these newly inducted systems in the Indian sugar industry.



(a)

(b)

Fig. 6. (a) V(phase) and I(line) for SRIM drive. (b) V(line) and I(line) for VFD and harmonic spectrum of current

IV. Proposed Three and Four-Level Inverter Based OEWIM

The problems discussed in the foregoing paragraphs associated with the conventional and newly inducted two-level inverter based VFD for cane preparation machines can be addressed by using MLI based OEWIM drives. Three main topologies of MLI are neutral-point clamped (NPC) inverters [27], flying capacitor (FC) inverters [28], and cascaded H-bridges (CHB) [29]. Fig. 7 shows the proposed OEWIM drive which is simple and cost-effective with each end fed with two-level inverter resulting in the inverter output voltage having three and four levels with 415V as the input voltage to the primary of the zig-zag transformer. MLIs of more than four levels feeding OEWIMs are reported in [30], but as the number of levels increases the complexity and cost of the hardware also increase. This arrangement, besides being simpler in design, will have a better voltage profile having lesser dV/dt stress, lower harmonics both in input current and inverter output voltage and reduced CMV.

A. The Power Circuit

As shown in Fig. 7, for input DC voltage to the inverters, three isolated DC sources are used. For DC-AC conversion, four 2-level inverters, two each for one OEWIM, are used. The three isolated DC sources are realised using a multi-winding isolation transformer with delta/zigzag-delta-zigzag configuration (delta with 0° phase shift and two zigzag windings having a phase shift of +/-20°). This results in an 18-pulse rectifier effect at primary and helps in mitigating input current harmonics [31]. Moreover, as only three rectifier units are used instead of four (two each of one OEWIM) thereby both the hardware and cost are reduced.

If two two-level voltage source inverters (VSIs) are operated with m=n=1/2 making dc-link voltage in the ratio 1:1 (typically $V_{dc}/2$ for both the inverters), a three-level output voltage can be obtained and operating the two VSIs with m=2/3 and n=1/3 making dc-link voltage, in the ratio of 2:1 (typically $2V_{dc}/3$ and $V_{dc}/3$), a four-level output voltage can be obtained [32]–[34]. In the present model for realizing the required dc-link voltage for the two cases viz. three-level and four-level voltage output, the turn ratio for different windings of the zig-zag transformer is given by (11) and (12) respectively.

$$N_p : N_{s1} : N'_{s1} : N_{s2} : N_{s3} : N'_{s3} = 1 : (1/2)x : (1/2)y : 1/2 : (1/2)x : (1/2)y \quad (11)$$

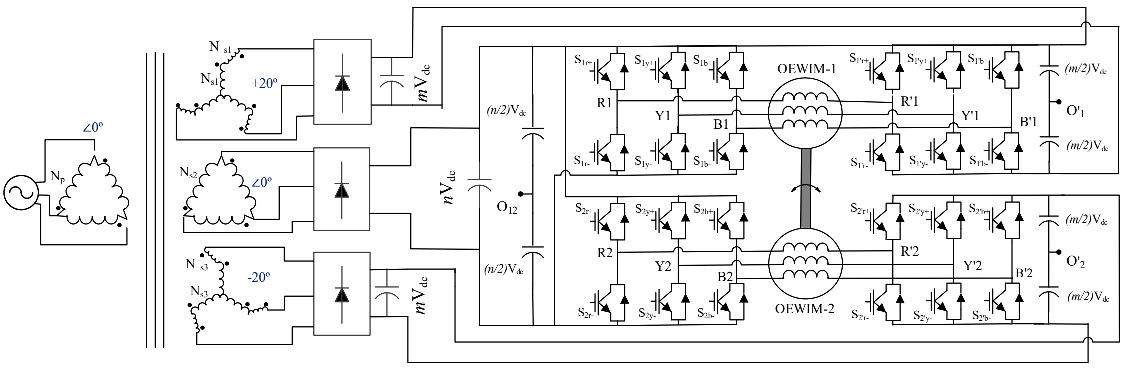


Fig. 7. The power circuit for the proposed OEWIM drive

$N_p : N_{s1} : N'_{s1} : N_{s2} : N_{s3} : N'_{s3} =$
$1 : (1/3)x : (1/3)y : 2/3 : (1/3)x : (1/3)y$ (12)

where, x = 1.136 and y = 0.395.

In Fig. 7, in the DC-AC converter part of the drive, Each of the coupled OEWIMs is fed with two 2-level voltage source inverters. $V_{R_1 O_{12}}$ and $V_{R'_1 O'_1}$ gives the pole voltage per phase with respect to the VSI-1 and VSI-1′ respectively, and $V_{R_2 O_{12}}$, and $V_{R'_2 O'_2}$ gives the pole voltage per phase with respect to VSI-2 and VSI-2′ The difference of pole voltage per phase for 'R' phase for OEWIM-1 and OEWIM-2 can be written as (13a) and (13b) respectively.

$$\Delta V_{R_1 R'_1} = V_{R'_1 O'_1} - V_{R_1 O_{12}} \quad (13a)$$

$$\Delta V_{R_2 R'_2} = V_{R'_2 O'_2} - V_{R_2 O_{12}} \quad (13b)$$

Therefore, the common mode voltage in terms of difference voltages for OEWIM-1 and OEWIM-2 is written as (14a) and (14b) respectively [35][36].

$$V_{c1} = \frac{1}{3}(\Delta V_{R_1 R'_1} + \Delta V_{Y_1 Y'_1} + \Delta V_{B_1 B'_1}) \quad (14a)$$

$$V_{c2} = \frac{1}{3}(\Delta V_{R_2 R'_2} + \Delta V_{Y_2 Y'_2} + \Delta V_{B_2 B'_2}) \quad (14b)$$

The phase voltage for 'R' phase for OEWIM-1 and OEWIM-2 is given by (15a) and (15b) respectively.

$$V_{R_1 R'_1} = \Delta V_{R_1 R'_1} - V_{c1} \quad (15a)$$

$$V_{R_2 R'_2} = \Delta V_{R_2 R'_2} - V_{c2} \quad (15b)$$

This gives a three level voltage output for m=n=1/2 and four level voltage output for m=2/3 and n=1/3. The voltage waveforms for two, three and four level inverter are shown in Fig. 9(b).

B. The Control Scheme

The application of the proposed drive comes under a low-dynamics category application, and hence, closed-loop volt/hertz control with slip regulation is implemented. Fig. 8 shows the control strategy for the proposed drive. The motor speed is compared with the command speed 'ω^*_r' and the error generates the slip frequency 'ω^*_{sl}' command through a P-I compensator and limiter. The slip is added to the feedback speed to generate the frequency and voltage command. The speed or frequency is the command signal and the proportional voltage signal 'V^*_s' is derived from it and is given by (15) so that the airgap flux remains constant [37][38].

$$V^*_s = \left(\frac{V_b}{\omega_b}\right)\omega^*_s \quad (15)$$

where, 'V_b' and 'ω_b' are the base voltage and base

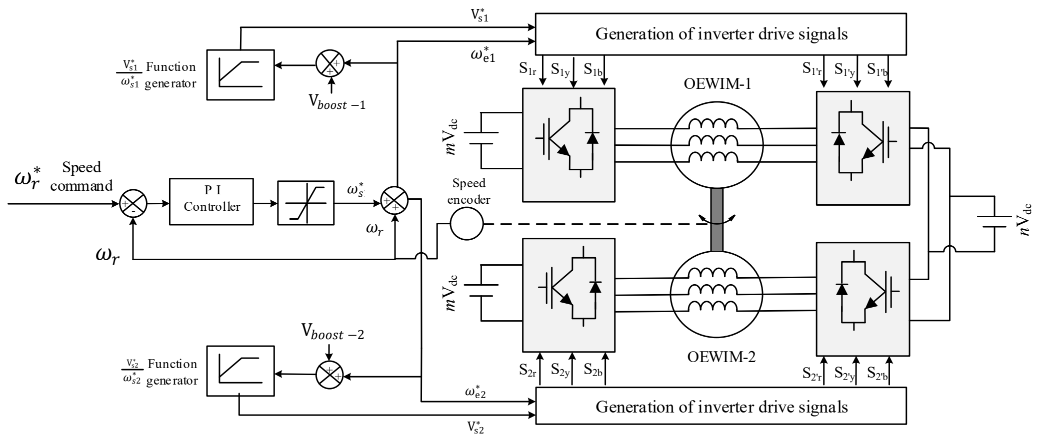


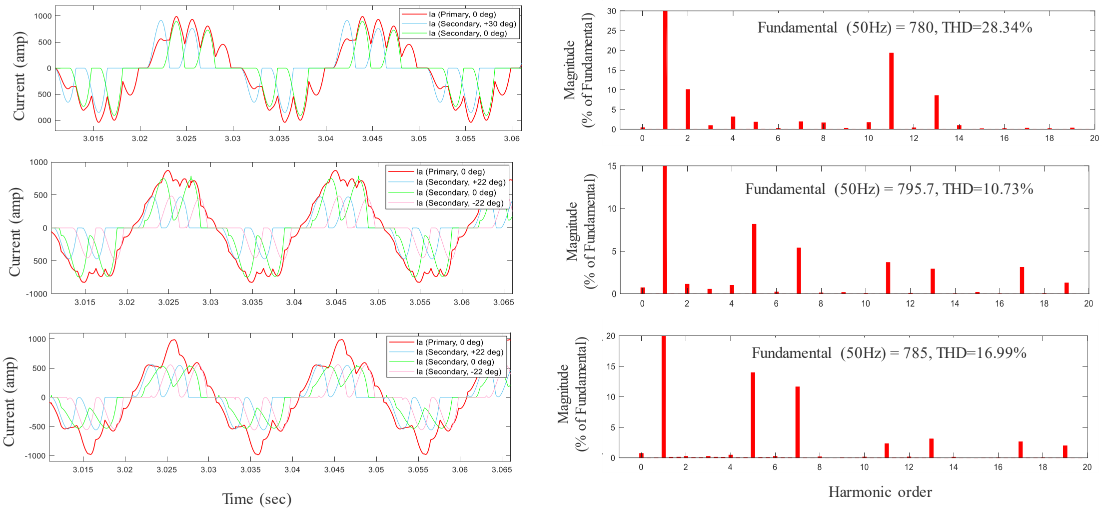
Fig. 8. Closed loop volt/hertz control scheme for the proposed OEWIM drive

angular frequency, respectively. At low frequencies due to the effect of the stator resistance and the necessity of rotor slip to produce torque across the stator resistance, it is necessary to boost voltage to compensate the voltage drop [39][40]. Therefore, a boost voltage is added to this signal so that flux does not decrease at low frequency. The coupling in the OEWCIM for shredder is considered rigid. In such rigidly coupled drives only one speed regulator and only one speed sensor may be sufficient [41].

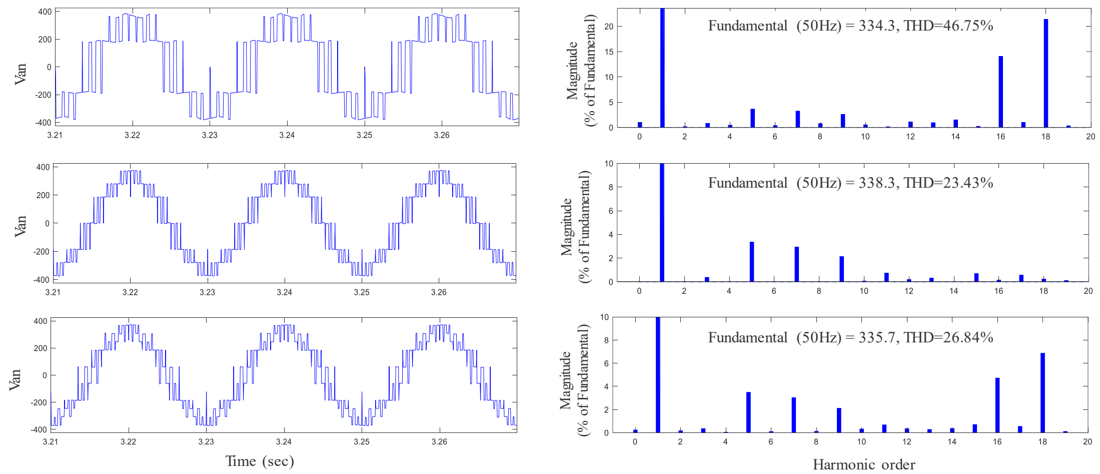
Performance-wise, the proposed drive is at par with respect to all other parameters and properties, viz. mitigation of surge in load current, reduced power loss in the rotor circuit, better load sharing and rpm regulation and reduced stopping time, as discussed earlier for the recently inducted two-level inverter based drives. But the results are further better in terms of reduction of harmonics in the input current to the drive as well as improvement in inverter output voltage profile for better dV/dt with reduced harmonics and reduced ill-effects of CMV for the machine being an OEWIM.

Fig. 9(a) shows the simulation results for the input current waveforms (at primary winding and individual secondary windings) along with its harmonic spectrum for the overall input current at primary and Fig. 9(b) shows the simulation results for the inverter output voltage waveform along with its harmonic spectrum for a three-level output voltage.

All three cases viz. 12- pulse rectifier with two-level inverter, 18-pulse rectifier with three-level inverter and 18-pulse rectifier with four-level inverter are shown in the figures. It can be seen that the THD in respect to both the input current and the inverter output voltage is improved by using the proposed drive. Circulating common-mode currents flow in open-end winding induction motors supplied by PWM drives if a single non-isolated source is used. However, if an open-end winding machine is fed using converters supplied from isolated voltage sources, the problem of circulating currents does not exist [42][43]. This circulating current has the effect of increasing losses in the stator resistance of the machine and is thus considered generally detrimental [36]. The proposed topology uses isolated three phase supplies which in turn gives isolated DC supply as required. The summary of the performance comparison of all the types of drives discussed is tabulated in Table I.



(a)



(b)

Figure 9. (a) Simulation results for the input current with harmonic spectrum. (b) Simulation results for the inverter output voltage with harmonic spectrum; *(top)* 12-pulse rectifier with two-level inverter, *(middle)* 18-pulse rectifier with three-level inverter, *(bottom)* 18-pulse rectifier with four-level inverter

TABLE I

COMPARISON SUMMARY OF THE IMPORTANT PARAMETERS

<table>
<tr><th rowspan="2"></th><th rowspan="2">Conventional SRIM Drive</th><th rowspan="2">Two-level inverter based VFD</th><th colspan="2">Proposed OEWIM Drive</th></tr>
<tr><th>3-level o/p volt</th><th>4-level o/p volt</th></tr>
<tr><td>Load current surge mitigation</td><td>Good[$€]</td><td>Good[#]</td><td colspan="2" rowspan="6">the performance is same as for the two-level inverter based VFD</td></tr>
<tr><td>Slip power Loss</td><td>8-12% [$£]</td><td>1-2%</td></tr>
<tr><td>Load sharing problem[€]</td><td>Problem persists</td><td>Problem addressed</td></tr>
<tr><td>RPM regulation[€]</td><td>Poor</td><td>Good</td></tr>
<tr><td>Stopping time during emergency</td><td>Longer time[&] (upto 30min)</td><td>Shorter time[# #] (with regeneration)</td></tr>
<tr><td>Power factor</td><td>Poor[£]</td><td>Improved[# # #]</td></tr>
<tr><td rowspan="2">THD (i/p current)</td><td rowspan="2">Not applicable</td><td>44.3% (directly connected to bus) [£]</td><td rowspan="2">10.73% (connected through zig-zag transformer)[$]</td><td rowspan="2">16.99% (connected through zig-zag transformer)[$]</td></tr>
<tr><td>28.34% (connected through phase shift transformer)[$]</td></tr>
<tr><td>THD (inverter o/p voltage)[$]</td><td>Not applicable</td><td>46.75%</td><td>23.43%</td><td>26.84%</td></tr>
<tr><td>dV/dt (inverter o/p voltage)[$]</td><td>Not applicable</td><td>High</td><td>Lower</td><td>Further lower</td></tr>
<tr><td>CMV[# # # #]</td><td>Not applicable</td><td>High</td><td colspan="2">Lower</td></tr>
</table>

[$] Deduced on the basis of simulation

[£] Screenshot/logged data saved in Fluke-345 power quality clamp meter from the sugar factories

[€] As obtained from DCS of the sugar factories mentioned in the paper

[&] A well-known phenomenon in sugar industry

[#] [38], [# #][18][19], [# # #][22], [# # # #][34][35]

V. CONCLUSION

A performance comparison of the existing drives (both the conventional, SRIM based, and the recently inducted, two-level inverter based VFD run SCIM drive) and the proposed three and four-level inverter based OEWIM drive is presented for the sugarcane preparation machine of the sugar industry. It is observed that while the conventional SRIM based drive effectively mitigates the surges in the load current with the help of slip resistance, but, it suffers from the demerits of power loss, about 8-12%, in the rotor circuit and there is an appreciable drop in rpm (up to 15%) which affects the consistency of the cane preparation. The recently inducted VFD based drives proved better in terms of rpm regulation and efficiency but such two-level inverter based drives are reported to have been suffering from ill-effects of CMV, harmonics and high dV/dt. The simulation results for the proposed drive proved to be further better in terms of reduced THD in input current, improved output voltage profile and reduction in harmonics in it.

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