An Efficient Scheme of Automation and Control for Conventional Cable Manufacturing Industry

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***Abstract*—In context of a 132 kV stranded conductor manufacturing plant, a unique automation scheme combining active energy front (AEF) along with variable frequency drives (VFDs) synchronization for achieving virtual electronic shaft aiming for simplified kinematics is implemented. A new design concept of tension control in take-up system and winding pitch control through autotraverse control was developed for unmanned operation. The outcome was optimum line speed and the power consumption linearly varying with increase in line speed, which is the core advantage of using synchronized line speed via VFD. There is no hidden energy loss in the system and the inertia of the whole driven system is also reduced. In case of high-voltage cable, the life expectancy depends upon the uniform pattern of lay length with compactness, and it is a significant achievement in terms of improvement in the product quality. The novelty of this work is the simultaneous implementation of various features in a single working setup. Conventional design of very long shaft attached with huge gearboxes is replaced with a virtual electronic shaft synchronizing seven VFDs attached to a very heavy inertial load. When considering the project size, there should be replacement of the high-maintenance-prone switchgears with AEF and LCL filters coupled with common dc bus; this helps in reducing the overall project cost. Self-controlled clean and quality power [below 3% of total harmonic distortion (THD)] feeding to utility network was achieved. Energy saving with improved power factor and higher efficiency is a significant achievement from this setup. Configurable automation software using the programmable logic control (PLC) and human machine interface (HMI) for flexible production was used as per market requirements (especially for 132-kV conductor sector). The scope of this paper is limited to the overview of implementing the automation scheme, energy savings, harmonics control, and other process control related to plants. The uniqueness of this experimental research project is generation and analysis of basic primary data (from September 2012 to current) and the publication available for this data. All activities from concepts to commissioning were systematically implemented and proved to be techno-economically viable.**

***Index Terms*—Active energy front (AEF), common dc bus, LCL filter, variable frequency drive (VFD).**

I. Introduction

A TYPICAL conventional stranding plant for cable manufacturing takes up approximately $300{-}400\,\mathrm{m}^2$ of space. The components involve a common line shaft, coupled with 7–10 gearboxes and linked to four cages such as capstan, take-up, payoff, and autotraverse units. Further, there are additional independent motors and gearbox setups responsible for a slow indexing speed. Hence, the line and cage speeds are limited as per gear stages involved. The mechanical setup, especially the gearboxes go through a lot of wear and tear. As a result, there are frequent breakdowns, which results in production downtimes. Moreover, the conventional setup dictates more than half of the input capital cost of the production unit. Furthermore, there is waste of huge energy through gearboxes, motors, and pneumatic brakes. The rotational kinetic energy stored is also wasted as heat with dominant machine running noise.

After 1985, there were improvements in using silicon controlled rectifier (SCR)-controlled dc drives and dc motors, highly suitable to provide high starting torque and good variation of line speeds (control range 1%–20%) with a better starting and run torque. From 1990 onward, induction motors became trendy, which were robust in construction and brushless in design when compared with their ac variable frequency drive (VFD) counterparts. With a widening spectrum of industrial growth, 55%–70% of energy share is attributed to electrical drives and motors [1]. World drive growth rate is 7%–10% per annum. de Almeida *et al.* [2], variable speed drives are considered to have the highest energy-saving potential and widely replacing the mechanical, hydraulic, and dc motor speed control system. Machines with high inertia, involving frequent start or stop with braking operations, and significant energy saving are realized.

The success of VFD application is based on the detailed application requirements and decision on drive ratings, considering environmental factors such as altitude, temperature, and types of driven loads, were clearly outlined [3]. Various types of control schemes for flux and slip control in induction motor were illustrated. The nonlinear nature was linearized by $d{-}q$ vector coordinate method similar to the armature and field control of a dc motor [4]. This resulted in reporting of the reliability of 77%. Apart from this, 82% of the users conducted harmonic analysis to ensure power supply conditions, and noise level of VFD at 1 m distance varied between 70 and 85 dB. The performance analysis of VFD was conducted [5]. 74% of the drives were with $12/6$ pulse design, while 23% were with $6/6$ pulse design. 95% of the drives had the provision of uninterruptable power supply (UPS) to reduce disturbance. 83% of the drives were wired to run motor directly without drive in case of breakdown. 70% of the drive failures were due to component failure, while 50% of the tripping due to under-voltage or over-voltage problem. There was a report of 40% fuse failure and 43% control card failures. 13% of problems were due to

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control power supply failure, protective settings at acceleration, and deceleration of drives.

The poor dynamic response of an induction motor, in any speed region, may be improved with direct torque control (DTC) technique by optimum adoption of switching and vector control, i.e., generation of electromagnetic torque in line with stator flux linkage [10].

In context of total harmonic current distortion (THDi), there was the comparative study done on the performance with an 18-pulse drive and a 6-pulse drive with passive harmonic filter (PHF) was conducted by Schneider Electric [11], and it was concluded that current harmonic mitigation is competitive. The constant tension in the wire-drawing process is of prime importance. Using MATLAB simulation, it was concluded that the performance of normal PID can be improved significantly by adding fuzzy PID control variable matrix [12]. Energy-saving concept directly reflects on cost saving, almost in all applications. It was validated by energy-saving analysis in a case study on seawater cooling pumps on the ship [15].

II. Strength and Weaknesses of Existing Conventional System

In an existing stranding plant, there is an inbuilt mechanical synchronization of all cages. High starting torque takes care of smooth start despite of large driven moment of inertia, which becomes higher under the unbalanced condition of cage (with one row loaded). There is a possibility of reverse run in case the motor fails to sustain the driven mass. The index gearbox (worm and worm wheel) acts as a brake to overcome reverse run rotational forces. This setup can be categorized as a conventional and simple system provided with mechanical kinetics involved. In this system, there are low harmonic distortion and low electromagnetic compatibility (EMC); however, the mechanical setup introduces other complex noise-related problems. Simple independent grounding for power and low-voltage control signals is a sufficient measure for controlling noise-free installation.

Based on the interaction with industries, an overview of a conventional setup is presented. There was a major issue related to overall energy transmission losses, as measured efficiency was below 65% for normal meshing of teeth angle, roughness, and toughness, profile of various sizes, and shapes of gears involved. Depending on models, the selectivity speed is limited to a maximum of 16 discrete working speeds and this can be changed only after shutdown of the complete unit. The quality of the product was normal, but there was no scope left for improvement and optimization of technology for quality and productivity. The main drive was derated, at least 150% higher due to start/stop issue of a high moment of inertia system. Typically, a 250-kW rated system was continuously consuming electricity, but its end usage is about 160 kW, leading to poor utilization of energy. During stopping with external pneumatic brake applied, there was stress and mechanical jerk causing torsion fatigue and gradually it leads to failure of bearings and damage to gear teethes due to heavy friction.

The maintenance cost was high due to rework and reverse engineering of gears to upkeep them within tolerance limits. This, in turn, requires heavy engineering workshop facilities such as heavy duty lathe, gear cutters, heat treatment plant, and gear-hobbing machines. Available hours for production were around 72% and it is observed that utilization of such setup is good for almost one-and-half year. The performance starts deteriorating after that and despite providing timely predictive, preventive maintenance inputs; the product life is approximately 7 years, which is 35% less in terms of “return on investment (ROI)” for a normal life of a machine. Heavy-driven moment of inertia leads to select a motor and VFD of higher size, at least 150% to the actual requirement. Indirectly, it leads to loading percentage around 60%, resulting in lowering the power factor and overall efficiency.

III. Problem Definition

There is a demand for rich featured plants, but the cost of investment required for that is comparatively too high. This requires choosing an alternate low-budget design to meet the technological gap. The investment, productivity, and sustainable process capable for getting quality product and energy savings are the major concerns which should meet our development drill. Based on different reviews of literature, survey, and various plant team interactions, and feasibility reports, the following objectives were formulated:

1) designing kinematics linked on VFD synchronization;
2) automation scheme, including software with human machine interface (HMI) for safe [16] and flexible product setup change;
3) energy saving, maintaining power quality, and harmonic mitigation below 3% total harmonic distortion (THD) with use of a unique active energy front (AEF) and LCL filter combination. LCL filter is more compact and capable of absorbing high-frequency harmonic current [13];
4) tension and pitch control with mechanical slip feedback by the encoder for precise conductor winding application.

IV. Methodology

A connection scheme of common dc bus is adopted for linking seven VFDs with an address and feedback signals for linking in automation scheme. The communication among them is in such a manner that all drives can be started, run, and controlled without violating the supply norms of the electrical network. These are synchronized to generate coupling like an electronic shaft with variable line speed of total machine. A unique interface with AEF and LCL is designed and implemented to avoid harmonic pollution to the electrical power feeder. Use of shielded motor cables with proper layouts are planned to reduce electrical noise, electro magnetic interference (EMI), and motor hunting with stabilized torque. Separate earth grounding was done for noise isolation. A design scheme is introduced to ensure automatic loading/unloading of bobbins, simplification of mechanical kinematics, and elimination of heavy gearboxes. It will take care for ergonometric standards for smooth operation and low fatigue.

A unique design of tension control for take up system and winding pitch control is implemented. These features make

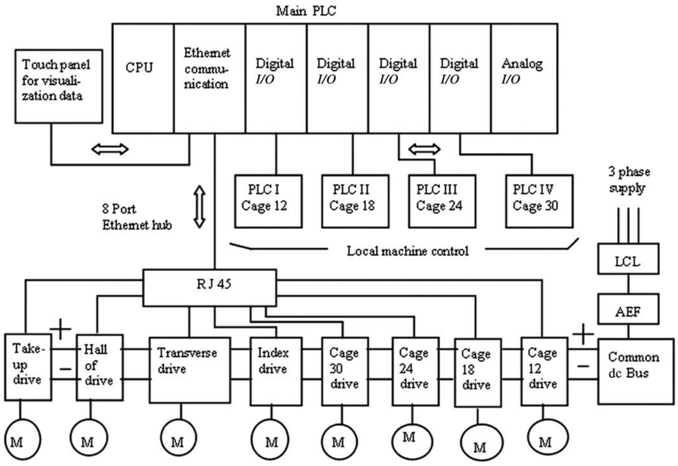

Fig. 1. Implemented schematic block diagram of automation, communication, and motion control by HMI and PLC for manufacturing stranded conductor.

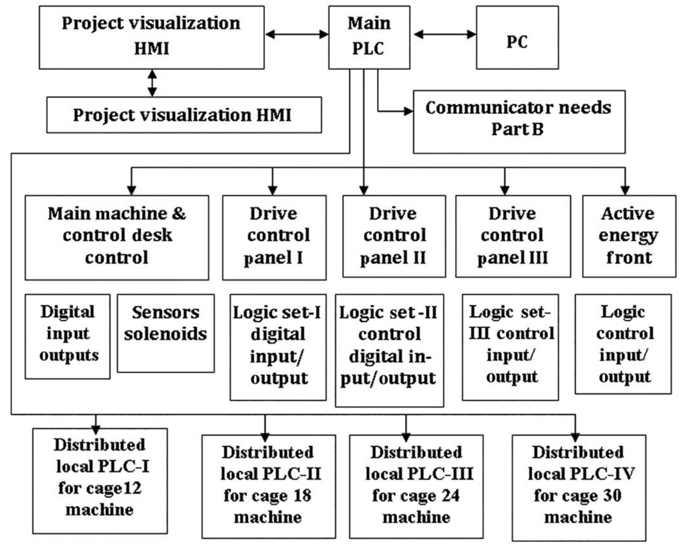

Fig. 2. Graphical layouts of needs of the project.

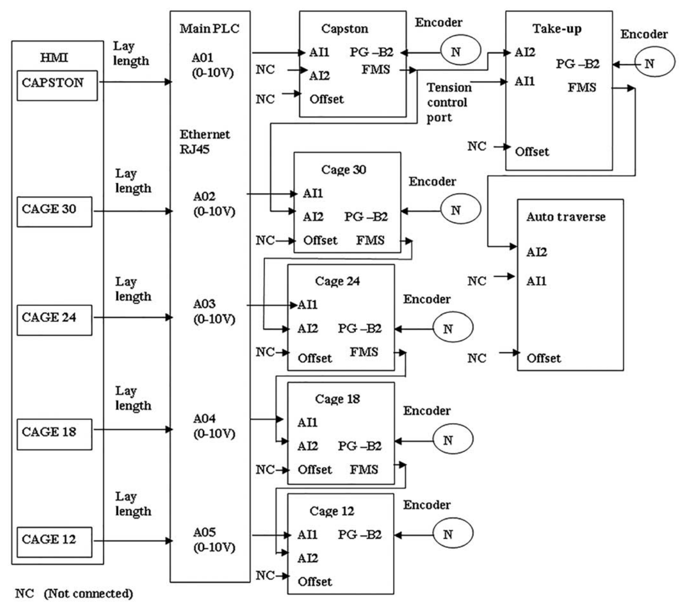

Fig. 3. Synchronization of electrical drives.

this system all together different than other system setups prevailing in the market. In compliance with findings of concept [6], help from vendors for product capability of drives, programmable logic control (PLC), HMI, and other important parts were matched with our application requirement of the process. Software needs, application description, exchange of data among various nodes, performance parameters, fault history, alarm conditions, downtime, usage time, energy consumption patterns, process limitation, and constraints were documented before the design stage.

A. *Implemented Automation Structure*

Fig. 1 shows an implemented schematic block diagram of automation structure [17], communication, and motion control using HMI and PLC for manufacturing stranded conductor. Fig. 2 lists a graphical layout of various activities involved in this project's life cycle. The automatic tension control of take-up was designed as closed-loop feedback from reel rotation through an encoder. Bobbin's loading/unloading was introduced to reduce setup time by hydraulic power control. The bobbin was opened and closed using electromechanical control.

HMI screens [18] are created considering production presetting parameter values, running status, product performance data, and creation of alarms and messages on faults. The PLC-related automation software [19] is written mostly in subroutines with local variables, which are modular, portable reusable after correlating with global variables.

B. *Synchronization of Drives*

In case of "online tuning" with vector control ac drive, knowledge of slip-constant was a necessary step, so that the errors between calculated torque and load torque can be minimized [7]. The foundation of the project lies on the precise synchronization of all eight drives starting from Capstan speed as master reference. The triggering point is the entry of "line speed in m/min" at the HMI. This is the speed at which cable conductor is to be produced. The line speed was based on the drawing speed of the main unit to control the whole of the line speed and allocate other units of reference of line speed, in turn [9]. The "data word" containing line speed information is sent to the main PLC where upon reading it gets converted into analog form at port AI1 (Fig. 3), which is a master reference to Capstan drive.

Energy management, to provide proportionate distribution and control for various rotating segments attached to virtual line shaft, was introduced, considering individual kinetic energy ($1/2\,\mathrm{MV}^2$) and moment of inertia that are involved. Following Table I is the basis of working out multiplying factors to offset kinetic energy buffering and slip control parameters of individual VFD and asynchronous motors of 12, 18, 24, and 30 cages. Based on 1500 synchronous rpm of an induction motor, the range of individual cage speeds was worked out as 153, 132,

TABLE I
TORQUE AND POWER CALCULATION FOR SELECTED MOTORS

Cage description	Weight (kg)	Radius (m)	RPM	Moment of inertia ($kg{\cdot}m^{-4}$)	Torque ($kg{\cdot}m$)	Power (kW)
Cage 12	4800 + 1800	0.683 + 0.3	210	122.383	134.567	44.169
Cage 18	7200 + 3000	0.683 + 0.3	180	184.95	174.311	49.04
Cage 24	9600 + 3600	0.683 + 0.3	150	244.765	192.238	45.07
Cage 30	12 800 + 4800	0.683 + 0.3	125	331.353	213.598	41.731
Capstan	4000	1.0	6.7	–	4000	53.333

121, and 101 rpm and for Haul off as 6.7 rpm. Based on torque calculations, motors were selected as per Table I.

When starting in the lower zone of frequent (say $1-5$ Hz), the starting current drawn is 135 A at 8 V for a 75-HP drive. Similarly, during stopping, the kinetic energy stored ($1/2\,\mathrm{MV}^2$) needs a quick transfer either into heat during blocking of magnetic motive force (MMF) of motor or as an electrical form back on to dc bus via the induction generator. This consideration needs at least 30% of margin in selecting VFD's rated load current as compared to motor size. The margin is to overcome under the voltage limit during the time of drawing, higher starting currents, and over voltage limit during the time of deceleration with the regenerative action of inductor motor. The energy transfer to utility network by AEF is started as soon as the dc bus voltage goes up by 2% (as set in our process).

C. Implementation of AEF

The 12-pulse rectifier frequently used in industries was an economic and simplified device for generating dc source, but not sufficient to interact with harmonic mitigation [14]. AEF unit along with special purpose filter (LCL) with recharging arrangement for dc bus was made.

Generation of the common dc bus was done by the bidirectional convertor and inverter units to which all seven number VFDs were connected. It acts as the common dc source with self-regulating features. The energy at a dc bus will be utilized by all drives during individual ramp up or acceleration and run in synchronized manner. During deceleration of machine with heavy moment of inertia, attached to individual motor drives, the mechanical energy in terms of braking shall be fed back to dc bus and in turn excess energy thus available at a dc bus shall be inverted and fed back to the utility network in order to keep the dc bus potential nearly constant. Here, in this manner, the energy that was getting dissipated through braking resistors or braking choppers and motor heating has been saved.

The inversion process makes AEF and VFD as nonlinear sources and contributes harmonics from 3rd, 5th, 7th, 9th, up to 25th order. These harmonics are source of pollution for supply network causing excessive heat losses in supply transformer and affecting other loads in the industry. Therefore, a specially designed LCL filter is employed to limit harmonics up to 5% as per IEEE519 standard [8]. This will ensure quality of power being fed back to the utility.

V. SCHEME FEATURES

Scheme features are as follows.

1) Elimination and/or minimization of gearboxes as per feasible scope.
2) Developing a virtual electronic shaft by synchronization of all the seven VFDs in such a manner that individual cage speeds shall be running according to line speed of conductor while maintaining lay-lengths well within defined accuracy band (replacement of mechanical common shaft and gears).
3) In order to reduce capital investment (by not using three-phase inductors and switchgear items in input supply circuit prior to each VFD), a common dc bus was established for supplying input power to all the drives.
4) Further, to ensure clean feeder supply, we introduced AEF, so that harmonics are filtered/mitigated with an additional advantage of harnessing energy saving by feeding back to the utility network. The excess energy is normally available during deceleration/braking because of the regenerative action of motor, using kinetic energy stored in high-inertia loads.
5) The common dc bus is a self-regulating one; hence, its stability prevention is lifeline to maintain smooth sustained synchronization. It also ensures that voltage dips are avoided, thereby avoiding the possibility of transmitting pulsating torque and hunting of asynchronous motor.
6) Automatic loading/unloading of Bobbins for entire row in a single shot is followed by indexed movement of next row position exactly at 90°, and thereby, it increases the available production house significantly.
7) Modular, portable reusable Software for PLC and HMI.

VI. EXPERIMENTAL RESULTS AND DISCUSSION

As per standard [8], for a supply system below 69 kV, the voltage THD value is 5% as shown in Figs. 4(b) and 5(b). In our case, the ratio is ISC/IL ≥ 20; therefore, threshold THiD limit is 5% as shown in Figs. 4(a) and 5(a). In other words, threshold is a cutoff point or bench mark above which harmonic level is not acceptable as per IEEE 519 standards [8]. Variables with their threshold values [Fig. 4(a) and (b)], like THiD being 1.8% at basic current value of 566.7 A and THvD as 3.3% at voltage value of 407 V, are directly adding to the strength and stability of Common dc bus. In Fig. 5(a) and (b), at point of common coupling (PCC), the significance and priority is given for clean voltage, which is validated by THvD threshold value as 3.3%. The threshold value of THiD is 99.7% including fifth- and seventh-order harmonic components with diminishing values at higher order harmonic progression.

Issue of THD was maintained below 3%. This fact has been verified in actual machinery setup. Thus, the application of AEF with common dc bus configuration acts as a local quality power conditioner. Harmonic simulation software such as HARMFLO, EMTP, and TACS are widely used. Power quality analyzer model HIKOI3196 is useful.

Table II gives a comparison of the magnitude of harmonic content in specific conditions and Table III shows how AEF

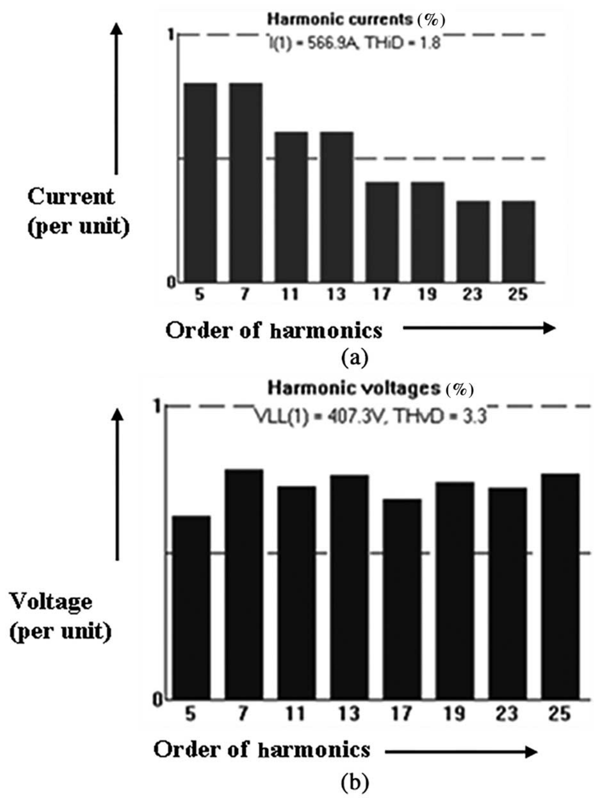

Fig. 4. (a) Harmonic currents at common dc bus bar. (b) Harmonic voltage at common dc bus bar.

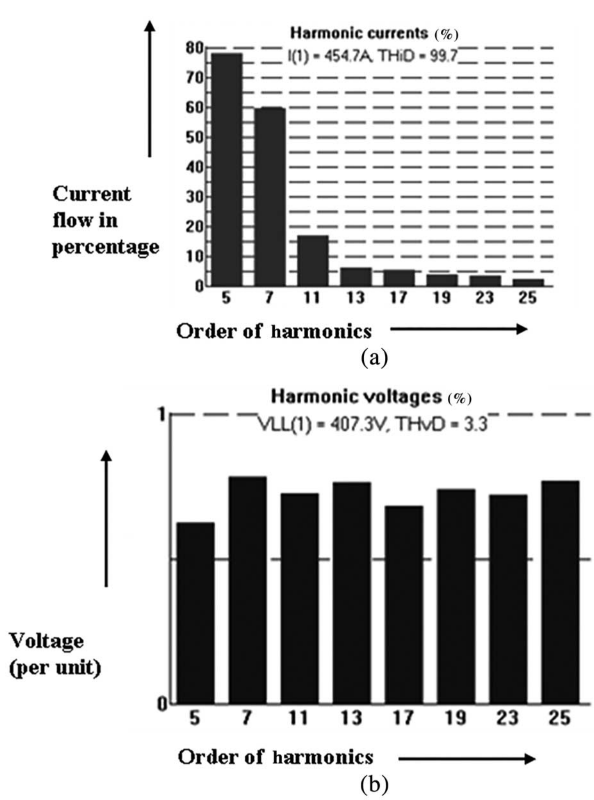

Fig. 5. (a) Harmonic current at transformer grid (PCC)/feeder point. (b) Harmonic voltage at transformer grid (PCC)/feeder point.

TABLE II
COMPARISON OF HARMONIC CONTENT MAGNITUDE

Type of configuration	% Cost comparison	Fundamental 100%	5th	7th	11th	13th	17th
6-Pulse rectifier without inductor	100	100	63	54	10	6.1	6.7
6-Pulse rectifier with inductor	120	100	30	12	8.9	5.6	4.4
12-Pulse rectifier with transformer	200	100	11	5.8	6.2	4.7	1.7
24-Pulse rectifier with 2/3 wound transformer	250	100	4	2.7	1.0	0.7	1.4
Active Insulated gate bipolar transistor (IGBT) rectifier/AEF LCL filter	250	100	2.6	3.4	3.0	0.1	2.1

TABLE III
SUMMARY OF RESULTS FOR COMMON LOAD USING AEF AND WITHOUT IT

Configuration	Current THD %	Voltage THD %	Power factor
6-Pulse rectifier	30	10	0.88
IGBT-based active filter	4	8	0.96

TABLE IV
CAPSTAN MOTOR AND SYSTEM EFFICIENCY (75 KW)

Line speed	kW at isolator	kW at AEF (dc bus)	kW at motor	Efficiency in %	
				Motor	System
3.24	7.47	7.33	6.75	92	90
7.92	8.30	17.93	16.5	92	90
13.32	30.76	29.83	27.75	93	90.2
18.72	43.23	41.93	39.0	93	90.2
24.12	55.99	54.03	50.25	93.2	89.9
27.36	63.04	60.96	57.04	93.5	90.4
29.7	77.16	75.0	70.65	94.2	91.5
33.12	74.49	72.63	69.01	95	92
40.32	80.96	78.5	74.61	95	92.3

stands among general schemes that are currently available. Not only it is significant in terms of electrical braking but rather more that it saves energy as well. It was found after a statistical study that the payback period for the AEF setup was 42 months.

A. Regenerative Energy Measurement

Kinetic energy stored during motion was measured in three different situations in a day such as normal stop, emergency stop, and optimized deceleration stop. The stop times were recorded as the primary data in a data logger. It was found that during a day's operation, braking energy in normal stop is measured as 1.58 kWh, in emergency stop as 0.71 kWh, and under decelerated stop condition as 2.46 kWh. This brings the cumulative yearly energy transfer to utility network up to 34,949

TABLE V
TRIAL RUN FOR CAGE 30 DRIVE (55 kW)

Line speed (m/min)	kW at isolator panel	kW at common dc Bus	Efficiency of AEF (%)	kW at motor	Efficiency of motor (%)	% Overall system efficiency
5.76	10.23	10.01	97.7	8.80	88	85.9
9.72	16.95	16.52	97.3	14.85	90	87.5
16.92	29.29	28.41	97.0	25.85	91	88.2
22.68	39.27	37.66	95.9	34.65	92	88.2
27.72	51.21	48.96	95.6	45.53	93	89.1
31.68	54.20	51.49	95.0	48.40	94	89.3
34.56	59.25	56.17	94.8	52.80	94	89.1
36.00	62.25	58.83	94.5	55.30	94	88.8

TABLE VI
COMPARISON OF EXISTING STRANDING SETUP AND IMPROVED SYSTEM

Parameters	Existing system	Improved system
Mechanical structure	85%	55%
Break down of set up	3.5%	0.8%
Sound level	≥80–90 db	Below 70 db
Energy	1.228 ton/hr	6.104 ton/hr
Speed limitation	10 – 16 fix speeds	Variable 5 – 38 m/min
Limitation in wide range of product requirement	Few patterns only	No limitation within set up capacity
loading of Bobbins	Manual 1.85 h	30 min
Frequent adjustments during production involved in winding	Difficult to manage by experience	Calculation data base with no trials
Setup time	Typical 2 h	30 min
Tension control with built-up diameter	Frequent correction	Auto adjustment
Manpower involved	5	4
Floor space occupied	4.5 × 60 m	3 × 60 m
Wire break stop time	40 s	Within 15 s
Breakage of conductor & rejection	6.0%	2.58%
Safety	Safe	More safe

TABLE VII
COST COMPARISON OF EXISTING STRANDING SETUP AND IMPROVED SYSTEM

S. no.	Parameters	Unit	Existing system	Improved system
1	Investment			
	Capital investment	Lakh	265	285
	Cost of transportations (typical)	Lakh	1.8	1.3
	Cost of foundation civil work	Lakh	8.5	4.5
	Cost of rejection	Lakh	4.46	1.25
2	Performance			
	Rate of production by weight	Tons/h	1.2	6.104
	Rate of production by cable length	km/h	2.1	2.156
3	Utilization per shift (8 h):			
	Setup time for change of product	Hours	2.3	0.45
	Load/unload time of bobbins	Hours	1.85	0.45
	Available production RUN time	Hours	6	7.5
5	Rejection percentage	%		2.58
7	Maintenance			
	Percentage of breakdown	%	3.5	1.35
	Annual cost of rework	Lakh	4.56	2.0
	Annual cost of spares	Lakh	12.5	3.0
	Annual cost of consumables	Lakh	7.5	1.85
8	Product life	Years	7–10	10–15

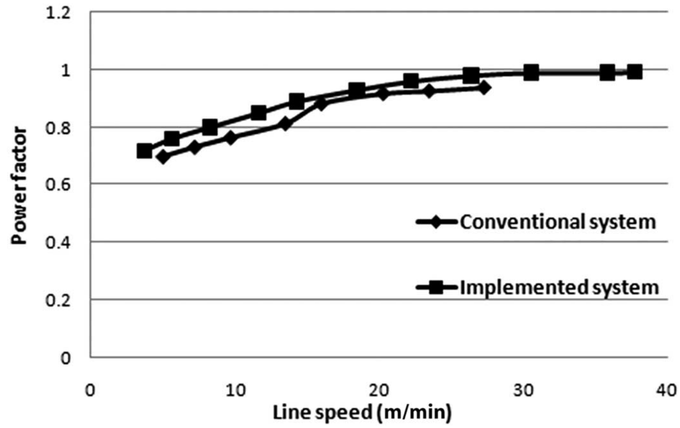

Fig. 6. Comparison of power factor variation with line speed in previous and implemented systems.

kWh, and the case study reveals that a payback period of the AEF and LCL setup was 28 months.

B. Setup Performance

Measurement of energy flow at various locations in different circuit zones was made (Table V). Further, during the total line run at various speeds, energy parameters such as kW, kVA, power factor, $\cos \Phi$, and true power factor (TPF) were recorded. Their interrelationship among the various variables is shown in the graphs. The quality of utility power is analyzed using harmonics analyzer to assess the impact of unwanted harmonics and the extent of their mitigation. At last, a quantification of energy saving was calculated.

1) Power Component Measurement at Various Speeds of Machine: Maximum line speed is given by

$$\begin{aligned} \text{Maximum line speed} &= \pi \mathrm{DN} \\ &= 3.14 \times 2.0\,\mathrm{m} \times 6\,\mathrm{RPM} \qquad (1) \\ &= 37.68\,\mathrm{m/min} \end{aligned}$$

From Fig. 6, it is observed that running the machine line below 22 m/min is not economical, as energy cost is increasing due to lower power factor. Second, there is an excess demand of reactive power responsible for iron core losses, cable losses, and excessive loading on feeding transformer. In other words, it reduces the utilization of installed capacity of various electrical equipments. The performance of implemented system is showing its improvement over existing one, despite the involvement of seven VFDs in the new system. The proposed system speed is 46% higher than the existing one, which implies higher productivity at lower energy cost.

Here in Fig. 7, the line speed of implemented system is much higher and still the energy consumption is comparatively lower. Further, power consumption is linearly varying with increase in line speed, which shows that it is economical to make any size of cable/conductor in full-speed range from 8.2 to 38 m/min. Heat losses in gearboxes are avoided and motor heat losses are minimized. The overall power consumption is significantly reduced. The production cost has come down by 3% due to energy saving alone. The linearity of the proposed

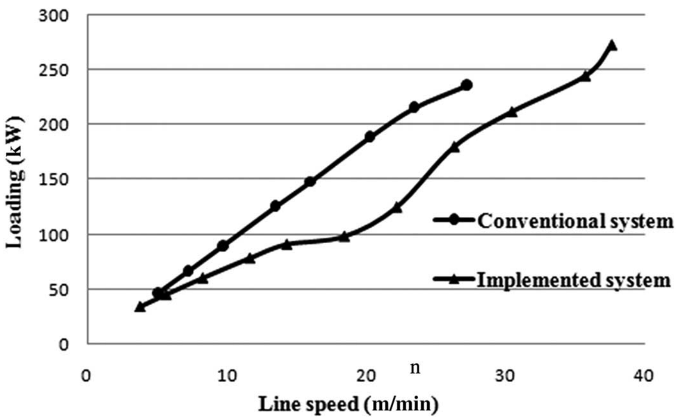

Fig. 7. Comparison of line speed variation with loading in both previous and implemented systems.

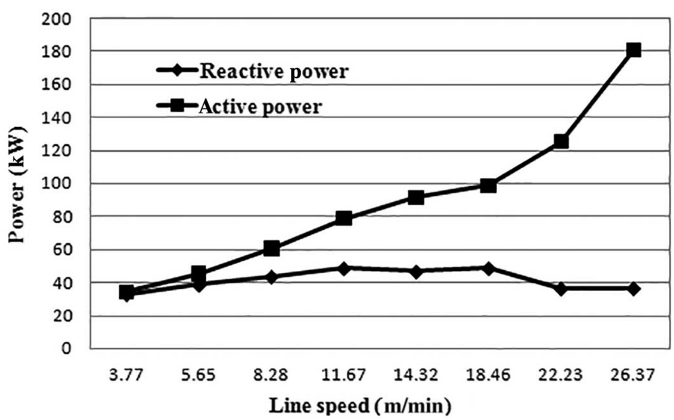

Fig. 8. Variation of reactive power and active powers with variation in line speed.

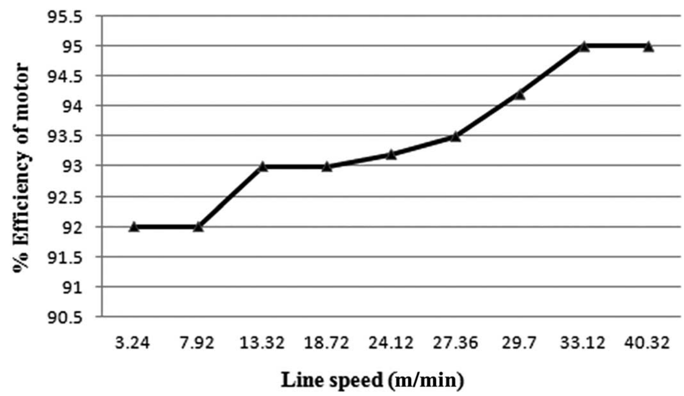

Fig. 9. Variation of efficiency of Capston motor with line speed.

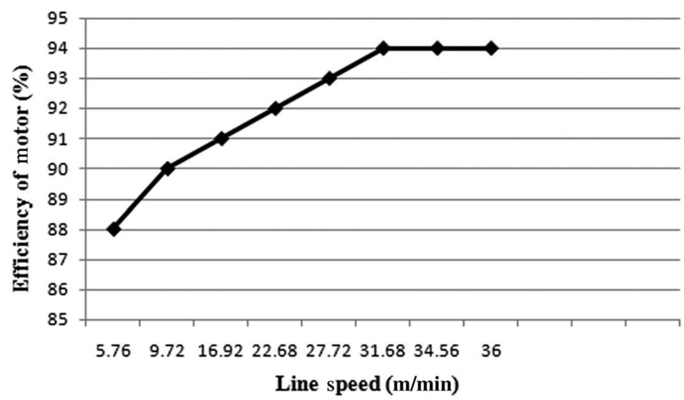

Fig. 10. Variation of efficiency of cage motor with line speed.

system graph proves nonexistence of hidden energy pockets in the entire system.

The current may be subdivided into components Id and Iq. Id is responsible for motor excitation including iron losses and secondary current and Iq is responsible for torque development. This theory explains the properties of this graph (Fig. 8); as interesting and useful for the fact that as line speed increases the kVAR is saturating and tends to decrease; means that the I_q component (responsible for torque) is increasing and I_d component (responsible for losses) is decreasing. In other words, there is gain in efficiency, power factor, and efficiency at nominal heat losses. There is in fact an energy gain, which is responsible for better kW/ton factor with lesser cost of production.

2) Motor and Drive Efficiency Measurement: An exercise for verification of mathematical assumptions made during the calculation of moment of inertia of various parts of machine and motor sizing/capacity is done based on experimental data recorded. The efficiency of the motor as shown in Table IV is achieved better than the expected figure of 90%. It can be further concluded safely that developed torque is steady (not pulsating) and incoming power to the motor is comparatively free from distortion and harmonic content.

Graph in Fig. 10 shows the efficiency of cage motor, which is a major driving part of the machine, and is quite steady and satisfactory ($\eta = 94\%$). The graph in Fig. 9 shows that in order to reduce losses, lower line speeds must be discouraged. Autotuning of the drive makes accurate access of motor design parameters such as winding resistance, leakage reactance, rotor inductance, slip value, iron losses, and no load current, and accordingly electronic overload is activated as per set percentage of rated load.

3) Overall Efficiency Assessment of the System: The power loss component in the system starts from cable losses, bus bar losses, and losses in the power electronic component, tendency of higher reactive power, increase in harmonic content due to higher switching frequency, and duty factor. As active power requirement in the motor increases, the corresponding increase in line current and frequencies leads to higher losses in all the above-mentioned components. From Fig. 11, there is an initial abrupt rise in loss component; however, as a percentage of higher active power (kW), it remains in the same order.

Measurement of power component, such as kW, kVAR, kVA, and power factor at isolator panel was taken, and a graphical trend shows that at 70% line speed, there is a break even for getting satisfied value of power factor. Below 49% of line speed, it is not economical to run the process for aluminum, but still it is useful for copper conductor carrying higher weight in this zone.

Variation of KW with line speed is nearly linear. The graphical trend of reactive and active power shows that at higher running speeds, reactive power values are freezing and tends to be lower. This means that better power factor and better efficiency eventually lead to energy saving. The behavior is

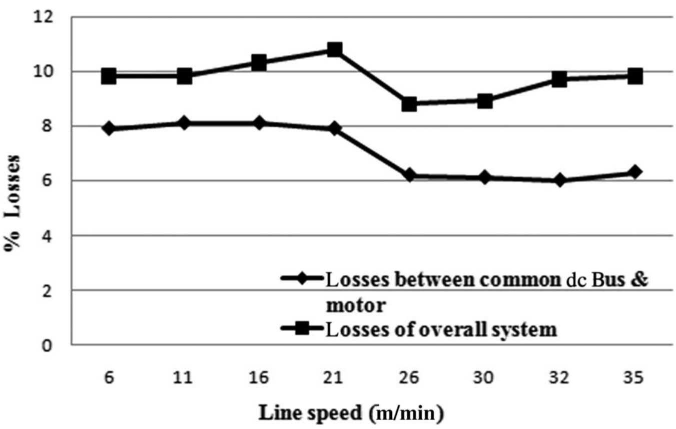

Fig. 11. Variation of cumulative losses and losses between dc bus with variation in line speed.

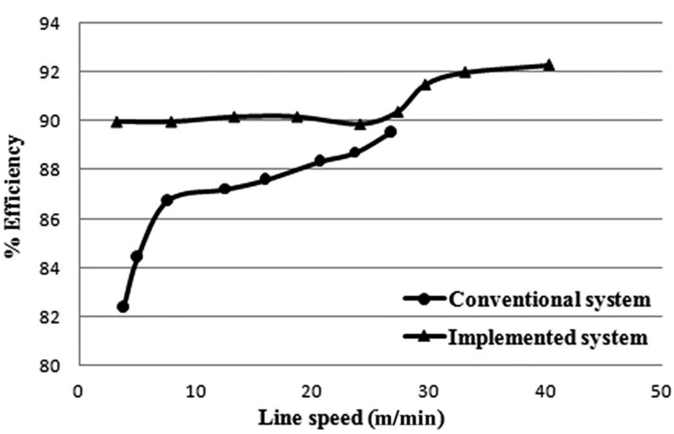

Fig. 12. Comparison between overall efficiency of previous system and implemented system with variation in line speed.

applicable for 75-kW capstan motor as well as for fourth number cage motors (55 kW). Overall system trends show that at least 60% loading is a necessity to achieve a breakeven point. However, above 85%, the losses are reduced, stable, and at minimum level.

At higher line speeds, overall efficiency is improved considerably up to 92% as shown in Fig. 12 as compared to the Conventional system. The level of kinetic energy and moment of inertia is raised by square ($1/2\,\mathrm{MV}^2$) and therefore, limitation of running at higher speed is only to ensure a safe working environment. Normally, our system is guarded during line run.

Apart from the analysis and comparison of technical components, it is worth to include economic comparison too as shown in Table VI and Table VII, so that feasibility of the total advance implemented system is validated.

An experimental result shows that the energy consumption ratio improved from 138.772 kWh/t to 51.65 kWh/ton. The productivity is increased from 1.228 /h to 6.104 t/h while maintaining THD below 3% as per IEEE Std. 519. Power factor is improved at load more than 40%–100%. As per quality norms, the rejection reduced from 6.0% to 2.58%. The energy saving was realized due to the elimination of six gearboxes (weighing approx. 18 000 kg). The second major source was additional regenerative energy stored at common dc bus and sending back to utility network after inversion process. The energy saving due to exclusive common dc bus part is 3%. This was measured by energizing a VFD separately with ac and dc sources.

Due to the presence of common dc bus, power factor was nearing unity (0.98–0.988–1.00), even under varying load conditions at different line speeds. Electrical energy transfer to utility network amounts to more than 36 000 units in a year. Therefore, the application of AEF unit is justified as harmonic mitigation unit and energy saver. However, there is one drawback of this scheme, which is linked with power failure during the running of the plant, i.e., not stopping precisely and influencing the lay length pattern. This needs alternative power backup for at least 20 s.

There were, seven ac drives (312 kW) along with AEF unit (460 kW) in our application and all these are nonlinear sources, generating harmonics to a large extent and complex in nature. However, due to overall system approach and unique connection scheme, it was observed that harmonics at PCC are below 3% THD. The placement of LCL filter is justified, as it has allowed only clean waveform to the utility network.

The motor temperature rise was found within $8^\circ\mathrm{C}$ above ambient conditions ($40^\circ\mathrm{C}$), which shows that overall efficiency of motors, in general, is very good (90.3%), and it is concluded that dragging torque, reactive currents, and iron losses are comparatively on the lower side.

The power factor of the motor is significantly better ($\mathrm{PF} = 0.85$). The sizing and kW rating of the motor is justified, as at normal working load, the efficiency of the motor was found above 0.94. Cable temperature of all the motors was within $0.8^\circ\mathrm{C}$, which means the cross sections used are adequate. Line synchronization of drives using combinations of analog inputs as the algebraic sum with 12 bit resolution was found within stability of 1.38% of set speed. Drive parameters were adjusted in proportion to their pace of moment of inertia in such a manner that speed change in master was followed linearly. The concept of high slips braking proves to be a good technique to control the overshoot of a drive during synchronization. The electrical cabinet temperature rise was $3.5^\circ\mathrm{C}$ above ambient. This indicates that electrical stress on power electronics, control transformer, LCL filter, AEF unit, PLC, drives, and HMI unit is well coordinated. Summing the reduction in load/unload time, setup time, and breakdown time, the productive hours have increased from 3.5 to 6.4 h in a day. As a result, productivity is increased approximately by 82%.

VII. Conclusion

The concept of the AEF connected to a common dc bus acts as a power conditioner and an energy-saving system. Additionally, along with LCL filter, it provides harmonic suppression below safe zone. Flexible electronic line shaft proved to be a better replacement of rigid long mechanical shaft and huge kinematics with a higher level of driven moment of inertia. Perfect lay length with good compact factor helps in the corona reduction in cable at 132 kV potential. There is a risk of collapse of virtual shaft and spoiling the conductor, at power failure. However, it is solved by electrolytic capacitor power backup devices.

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