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Optimum Operation of Low Voltage Variable-Frequency Drives to Improve the Performance of HVAC Chiller System

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Summary: A tremendous increase in the industrial and commercial applications of low voltage variable frequency drives (VFD) has been observed in the last decades. VFD is mainly used for significant energy saving and reliable speed control of industrial motors in an electrical system. Power quality issues are becoming more apparent due to the installation of these modern technologies based on variable frequency. In this paper, the optimal operation of VFD fed motors has been studied to improve the performance of heating, ventilation and air conditioning (HVAC) centrifugal chiller system. A non-intrusive technique is used to investigate the total harmonic distortion (THD), power factor, distortion loss ratio, temperature, and efficiency effects by varying load and speed ratios of VFD systems. The measurement of these parameters has been carried out by performing a series of experiments under variable operating conditions. A binomial relation has been found between the various performance parameters and the operating conditions. Based on experimental results, optimal operating conditions have been proposed and implemented for the VFD system. Results have been compared with existing operating conditions that show a 67.6% reduction in the THD, 28.9% improvement in the power factor, 54.7% reduction in distortion loss ratio and 24.6% improvement in the efficiency of the low voltage VFD system.

KEYWORDS: Harmonic distortion, HVAC, mathematical modeling, optimum operation, performance analysis, variable frequency drives.

List of Symbols and Abbreviations:

VFD	Variable frequency drives
HVAC	Heating, ventilation and air Conditioning
THD	Total harmonic distortion
PQA	Power quality analyzer
DLR	Distortion loss ratio
PCC	Point of common coupling
MFL	Module full load capacity
SFL	Set full load capacity
MLR	Module load ratio
SLR	Set load ratio
MAPE	mean absolute percentage error
P_l	Total line losses
I_h	Harmonic current
V_h	Harmonic voltages
Y_h	Harmonic admittance
P_h	Harmonic line losses
R_h	Harmonic resistance
η	Motor efficiency
P_i	Input power
P_o	Output power
i	Number of modules
j	Number of sets

1 INTRODUCTION

The mechanical and pneumatic systems installed in the industries worldwide are being shifted towards electrical motors to reduce the operational cost and energy consumption. Being a major shareholder of global electrical energy, it is highly desirable to achieve the maximum possible efficiency of motors. Variable frequency drives (VFD) is a popular technology that is used to control the operation of induction motors while maintaining high-efficiency operation. On one side, these drives improve the system efficiency by reducing the stresses produced by inrush current on stator winding and allow the soft start of motors [1-3]. But on the other side, the unmanaged operation of VFD not only causes the poor performance of rotating machines but may also lead to their permanent damage over the prolonged operation time. The non-sinusoidal currents produced by VFD contain significant high-frequency components in addition to the fundamental frequency of the power grid [4, 5]. Since VFD installations are gradually increasing day by day, thereby the modern power system is becoming more prone to power quality and electromagnetic interference (EMI) related problems [6]. To protect the power system from degradation, it is important to keep the harmonics level below the standardized tolerable limits and managing the optimum operation of the VFD system [7, 8].

The heating, ventilation and air conditioning system (HVAC) consumes about 40% to 50% of the total energy in the commercial and residential buildings [9]. Being a dominant energy load, the performance of the HVAC system influences the overall efficiency of the power system. Therefore, it is important to investigate the performance of the HVAC system. In air-cooled centrifugal water chiller systems, rotating machines powered by VFD are widely used in compressors, condenser fan motors, and water pumps. The percentage loading of installed compressors depends upon the outlet temperature of chilled water during the operation of the HVAC system. Further, the percentage loading of compressor cooling fans depends upon the loading conditions of the compressors. To reduce the power consumption, the VFD system runs at partial load and partial speed conditions when the outlet water temperature is either achieved or set at a higher value. This partial load and partial speed operation of the drives-based system lead to poor performance, thus affecting the system efficiency. Based on experimental work, optimum operation of the VFD system is proposed that provide a better performance, cost-effective and have less wear and tear with improved process control.

The rest of the paper is organized as follows: Section I presents the literature review and the main contribution. Section II an overview of the problem under investigation. Section III presents the methodology for the estimation and evaluation of the performance parameters for the optimum operation of low voltage VFD fed motors. In Section IV, the experimental test setup is detailed. In section V the measurements of performance parameters have been carried out on the experimental test setup under variable operating conditions. Based on the experimental results, correlations between performance parameters and operating conditions have been developed. Further, the optimum operating conditions are proposed and compared with the existing operating conditions. In section V, conclusions are drawn based on experimental results.

2 LITERATURE REVIEW

In previous studies, significant progress to investigate the overall performance of the VFD system and available solutions for its improvement has been achieved in the last

25 years [10-12]. For instance, the performance of the VFD system is influenced by power quality, which is examined in [13, 14]. References [15, 16] presented the effect of VFD on the performance of rotating machines by considering the power and efficiency issues. Similarly, [17, 18] investigated the motor performance and method for determining the efficiency based on the operational parameters i.e., load ratio and speed ratio. The reduction in the efficiency of VFD fed motor under variable loading has been investigated in [18, 19] and methods for the improvement of the efficiency of VFD systems have been studied in [20].

However, to the best of our knowledge, none of the existing literature developed mathematical models to quantify the impact of variable loading conditions, i.e. load ratio and speed ratio on various performance parameters including THD, power factor, distortion losses and, the efficiency. Based on long-time operation in the field experiments, the correlations established between variable operating conditions and the performance parameters are utilized for a quick estimation of the performance of the VFD system. Alternatively, the main contribution in this work is not only limited to the development of relations for the quantification of the impact of various loading conditions on the performance of VFD system, but a mechanism is also presented for the selection of optimum operating conditions to achieve better efficiency, reliability, and enhanced power quality. The proposed optimal operating conditions are implemented for the VFD system installed in the HVAC chiller. The plausibility of the proposed method is established by comparing the performance parameters and the energy consumption under both existing and proposed optimum operating conditions.

3 METHODOLOGY

The unmanaged variable load and speed operation of VFD lead to the poor performance of the HVAC system which subsequently enhances the maintenance cost. To enhance the operational efficiency and to reduce the power quality problems, a non-intrusive testing platform is employed and is shown in Fig. 1. Consider a VFD based system used in HVAC chillers in which a motor is attached with a fan assembly. Power quality analyzer (PQA) is used for online condition monitoring of the power system at variable load and speed operations. Torque and speed of the motor are measured with the help of sensors fixed at the motor shaft. The winding temperature of the motor is measured through an infrared thermometer sensor. The load and frequency are monitored through the VFD display.

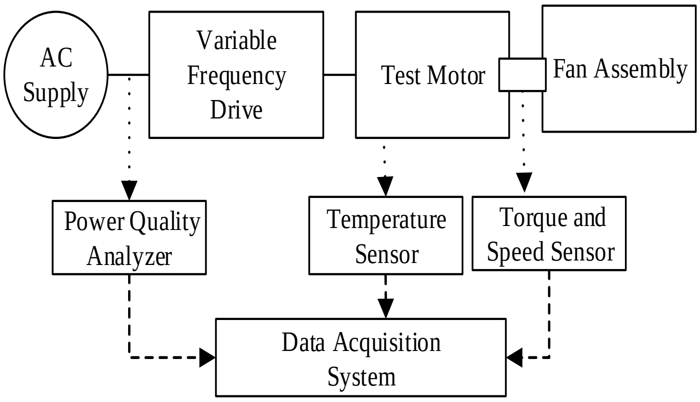

Figure 1. Generalized testing diagram for VFD fed motor.

The contribution of the harmonic component in total line losses is an important parameter to investigate the effect of variable load and speed ratios on the losses produced by the VFD system. For this purpose, the measurement of total line losses (P_l) can be directly made using PQA. The calculation of line losses produced due to harmonics components can be made by considering two nodes (i, j) of the system. The current flowing between node-i and node-j is represented by (1).

$$I_h\ (i,j) = [(V_h\,(i) - V_h\,(j)] \times Y_h(i,j) \qquad (1)$$

Where, $I_h\,(i, j)$ is the harmonic current from node-i to node-j. $V_h\ (i)$ and $V_h\ (j)$ are the harmonic voltages at node-i and node-j respectively. $Y_h\,(i, j)$ is the harmonic admittance between nodes (i and j). The harmonic current can be calculated either for all harmonic orders or specific to any harmonic component of interest through PQA. The corresponding harmonic line losses can be calculated as given in (2).

$$P_{h,l} = I_h^2\ (i,j) \times R_h\ (i,j) \qquad (2)$$

Where, $P_{h,l}$ is the harmonic line losses and $R_h\ (i,j)$ is the harmonic resistance between nodes (i and j). Distortion loss ratio (DLR), which is calculated by dividing the line loss produced due to harmonics with the total line loss as given in (3).

$$DLR = \frac{P_{h,l}}{P_l} \qquad (3)$$

Motor efficiency *(η)* during on-site testing can be estimated by many methods as discussed in [21, 22]. The simplest method to define the η is the ratio of output power to the input power as expressed by Equation (4).

$$\eta = \frac{P_o}{P_i} \times 100 \quad (4)$$

where P_i and P_o are the input and output power of the motor respectively. P_i can be measured using PQA and P_o can be measured indirectly by measuring the speed of the motor and torque of the shaft [18].

The overall methodology used in this paper is based on the field experimental results, as shown in Figure 2. Consider an HVAC chiller system selected for investigating the impact of variable operating conditions on the performance of a low voltage VFD system. The HVAC system consisting of *i* number of modules and *j* number of sets of compressors and VFD fed fans installed in each module. Harmonic losses measurements can be carried out in voltage and current waveforms of VFD systems, after achieving the thermal stability. The performance of VFD systems can be studied by observing efficiency, power factor, THD, temperature and distortion loss ratio under variable load and speed ratios. Based on experimental findings, the relationships between these performance parameters and variable operating conditions may be found through curve fitting. Experiments can be repeated after implementing the proposed operational logic to compare with the existing operating conditions. The results can be validated based on experimental findings and improvement in the performance parameters may be calculated.

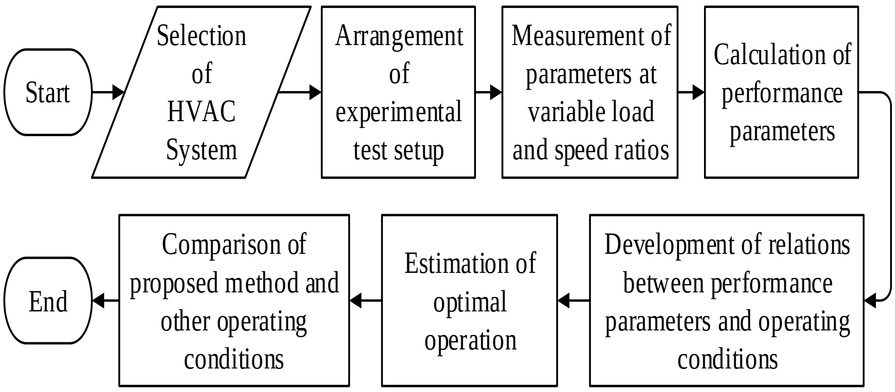

Figure 2. Flowchart representing the methodology adopted in this research.

4 EXPERIMENTAL TEST SETUP

In order to analyze the methodology mentioned in the previous section, we have considered an air-cooled centrifugal water chiller having an operational capacity of 345 tons as shown in Figure 3. The chiller consisted of four modules *(i=4)* and each module comprised two sets *(j=2)* of soft starter-based compressor motors having the capacity of 88 kW each. Two VFD systems were installed in each module for condenser exhaust fans having a capacity of 55 kW each. A capacitor bank of 450 kVAR was installed near the chiller load. The detailed specification of vital components installed in the HVAC chiller system is given in Table 1.

The power quality can be better analyzed by THD which is the accumulation of all harmonic components. In this research work, various locations were taken as a common point of coupling (PCC) and testing was carried out according to the testing arrangements shown in Figure 1. The humidity and temperature of chiller intake fresh air are maintained (60 RH and 30 ^{0}C) to avoid the impact of environmental conditions on the experiments.

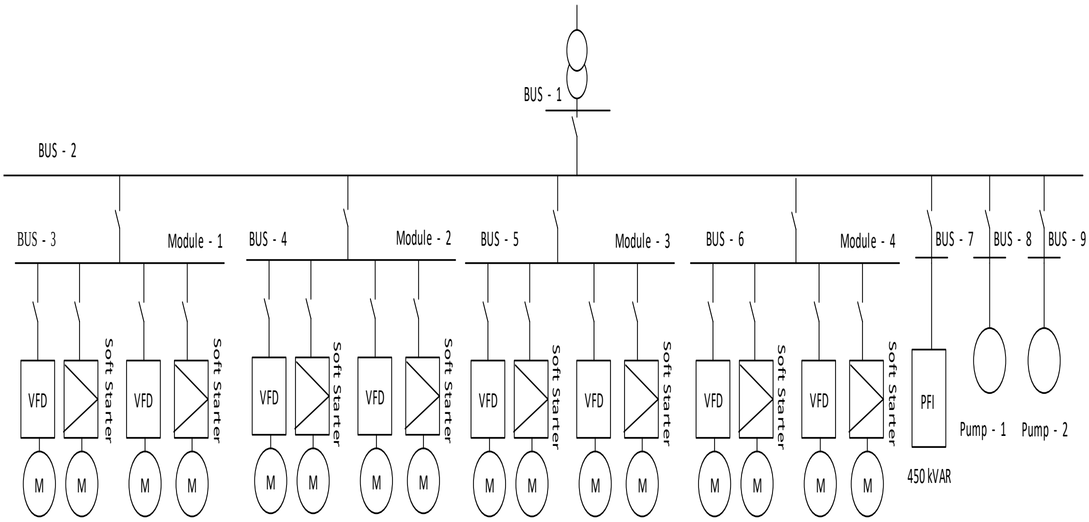

Figure 3. Single line diagram of 345 tons HVAC chiller system consisting of four modules.

Table 1. The detailed specification of electric components installed in the HVAC chiller system.

Description	Specification
HVAC Chiller	Air-cooled centrifugal water Chiller, 345 tons capacity comprised of 4 modules (350 kW each) and 2 sets of compressors along with VFD fed fans in each module, nominal airflow: 136000 to 141000 m^3/h, water flow: 48000 ltr/hr Make: INTERKLIMA
Soft starter	90 kW, 400 V, 50 Hz frequency, 160 A, Model: DS7-34
Compressor Motor	88 kW, 3 phase, delta connection, maximum current 205/215 A 400-460 volts, 50/60 Hz frequency, Make: COMER
Variable frequency drive (VFD)	55 kW, 3 phase, delta connection, 380 V to 690 V, input frequency: 50 Hz, Make: ABB

VFD fed motor	55 kW, 3 phase, delta connection, 400 V, 4 poles, 99.8 A, IP55, Ins. Class F, rated efficiency: 96%, power factor: 0.85, input frequency: 50 Hz, Make: ABB

5 MEASUREMENTS AND RESULTS

4.1 Harmonics Analysis at Different Locations Under Variable Load and Speed Conditions

The impact of variable load and speed conditions on the harmonics components was investigated to estimate the performance of the HVAC system. A series of experiments were performed to obtain results at variable operational parameters. In the first experiment, the HVAC chiller system was energized manually to measure the THD at full load. The harmonic spectrums were logged at Bus-2 for the first thirteen harmonic orders. It was observed that both THD_v and THD_i are influenced by 5^{th} and 7^{th} harmonic components, which are the most dominant. Harmonic spectrums for both THD_v and THD_i are shown in Figure 4.

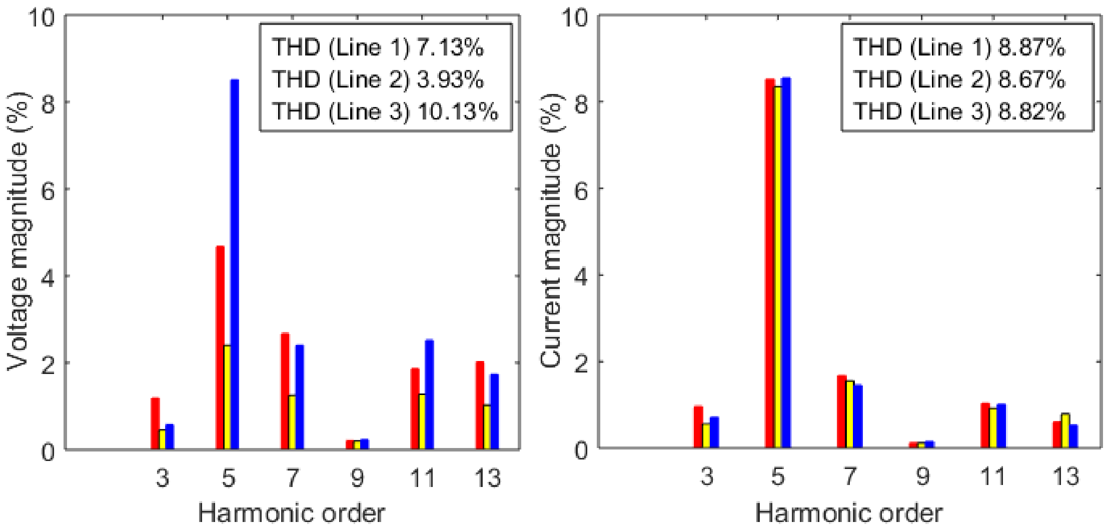

Figure 4. Harmonic spectrums at Bus-2 when the system is operating at full capacity (a) Voltage, (b) current.

In the second experiment, harmonic analyses were performed at Bus-3, Bus-4, Bus-5, and Bus-6 to measure the harmonic distortion for individual modules while the other three modules remained switched off. By considering only THD_i , current harmonic spectrums for module-1 and Module-2 are depicted in Figure 5.

Comparing Figures 4 and 5, it has been observed that the harmonic components in the individual module are greater than the harmonic components calculated for the complete chiller system. The reduction in the harmonic contents is due to the additional linear load during the complete chiller system operation.

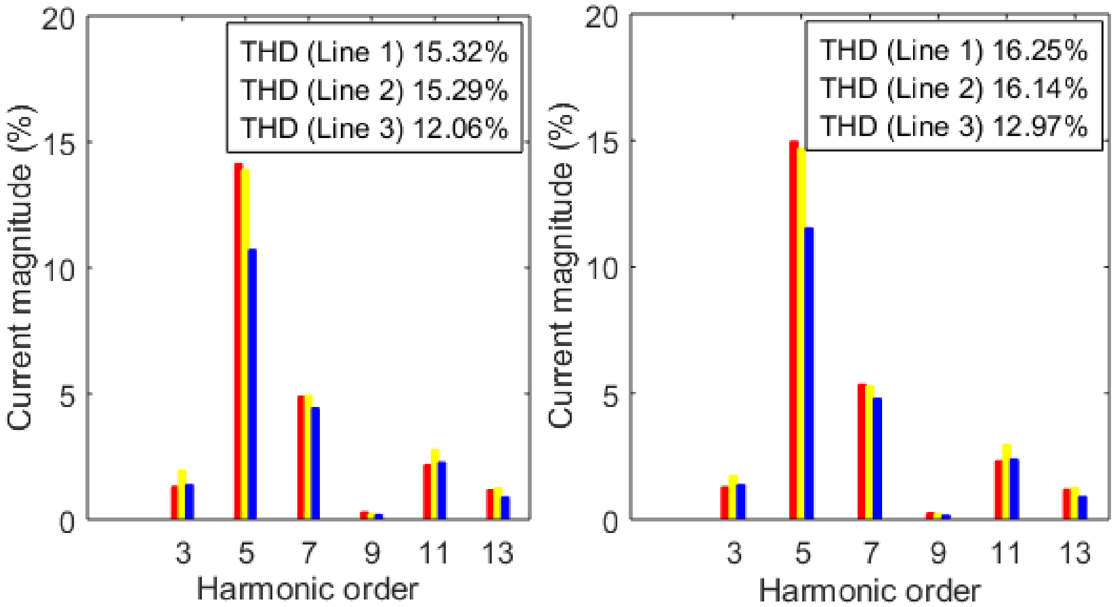

Figure 5. Current harmonic spectrums for individual module operating at full capacity (a) Module-1, (b) Module-2.

In the third experiment, on-line monitoring of the system was carried out by energizing the system in an automatic mode of operation for 60 hours. The harmonic contents were measured on an hourly basis. The value of phase voltage (V_{rms}) varied from 230 V to 257 V and fundamental current (I_{rms}) varied from 70 A to 1100 A. THD_v and THD_i calculated during different time intervals have the inverse relation with I_{rms}, as shown in Figures 6 and 7. It was observed that if the VFD system is continuously derived at low load conditions, then harmonic components and overall THD increase. A significant increase was observed specifically in THD_i. In Figure 7, THD_i was started from 10% when I_{rms} was 1050 A. THD_i mostly consisted of 5^{th} and 7^{th} harmonic components of current. At a very low percentage loading of about 80 A, the THD_i was increased up to 40% with 32% of the 5^{th} harmonic component and 18% of the 7^{th} harmonic component.

The amount of THD_v and THD_i measured at low percentage loading can cause the poor performance of VFD fed motor due to the overheating of the system. The increase in internal temperature reduces the life of the insulation of motors. The overall losses due to harmonic components are also increased which reduces the efficiency of the system, as explained in the subsequent section.

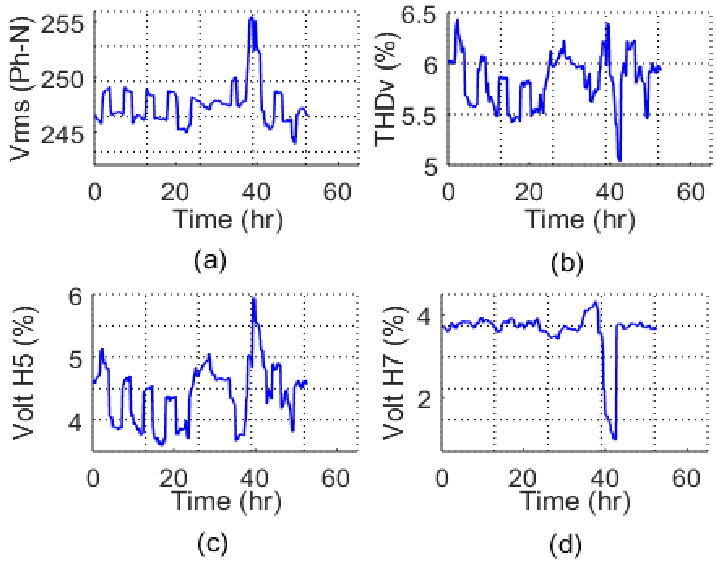

Figure 6. On-line monitoring of voltage harmonic spectrum with dominant components under different loading conditions, (a) V_{rms} (Phase to Neutral), (b) THD_v, (c) Volt H5, (d) Volt H7.

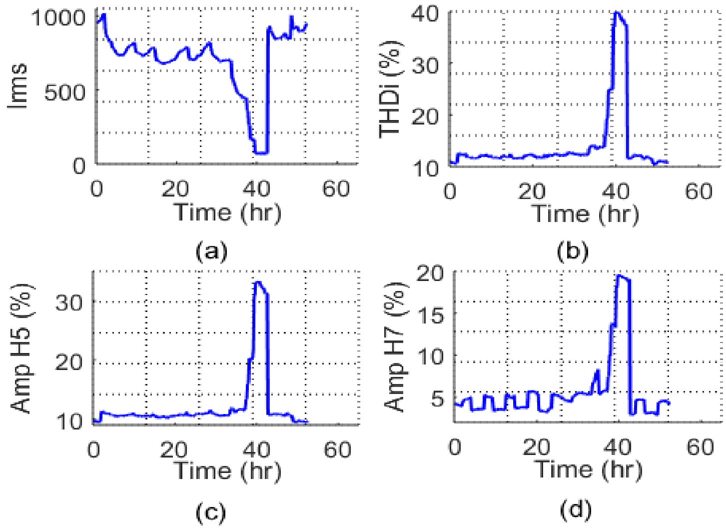

Figure 7. On-line monitoring of current harmonic spectrum with dominant components under different loading conditions, (a) I_{rms}, (b) THD_i, (c) Amp H5 and (d) Amp H7.

4.2 Measurement of Performance Parameters Under Variable Operating Conditions

Two VFD systems from two different modules were selected to measure the performance parameters. The impact of variable loading conditions on THD was observed. Figure 8 shows the variation of THD_v and THD_i under different loading conditions when only a single VFD system was energized at a time and other motors remained power off. Both THD_v and THD_i were increased when the load ratio of VFD was decreased.

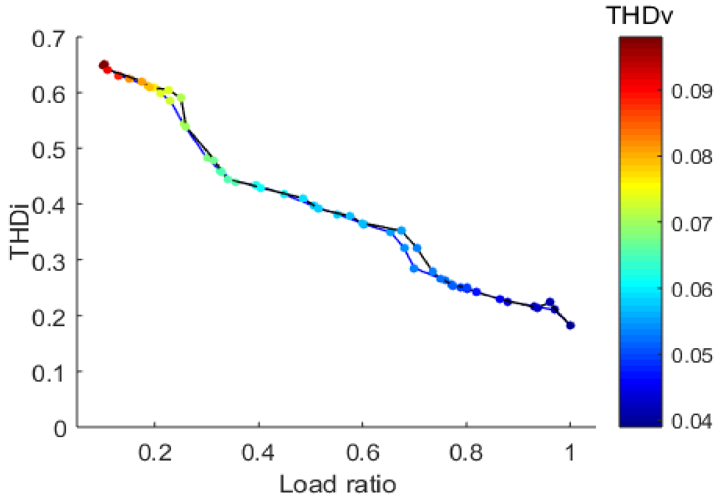

Figure 8. Relationship between THD_i, THD_v and load ratio when only a single VFD system is energized at a time.

Further, the variations in temperature were observed at a variable speed ratio and constant load ratio. The experiments were performed for 15 hours on both VFD systems and a total of 30 measurements were recorded. Thermistor motor protection relays were installed in both motor and the tolerable range was adjusted up to 145℃. Figure 9 shows that the temperature is increased by decreasing the speed ratio at a constant load ratio.

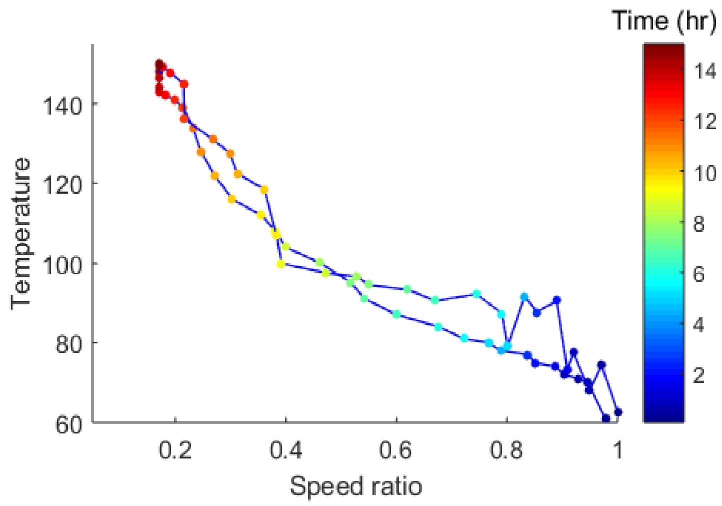

Figure 9. Relationship between the temperature and speed ratio at different time intervals.

From the above experiments, it was observed that the cooling fan used for motor winding is directly coupled with the rotor shaft. When motor fed by VFD is operated at a lower speed ratio, the speed of the cooling fan is also reduced, thus reducing its effectiveness. When VFD was started, the temperature of the motor was increased until the motor reached rated load and speed ratios. The speed of the VFD was changed manually and measurements were recorded. When the speed ratio of the motor was reduced up to 0.5 at different intervals, the variation in temperature was increased. At a speed ratio of 0.17, the temperature of the motor winding was increased up to 142℃. The speed ratio was made constant at this level. Further, the variations in temperature due to insufficient cooling were seen until the thermal protection installed for the motor was operated due to excessive heat.

Other aspects of variable loading conditions and speed ratios of VFD systems were observed. Figure 10 shows the variation of power factor of both VFD fed motors against the change in load ratio at a variable speed ratio. It was observed that the power factor is reduced during partial loading conditions. Thus, it is important to investigate the impact of variable operating conditions on distortion losses because of the reduction in the power factor increases the overall losses of the system [23].

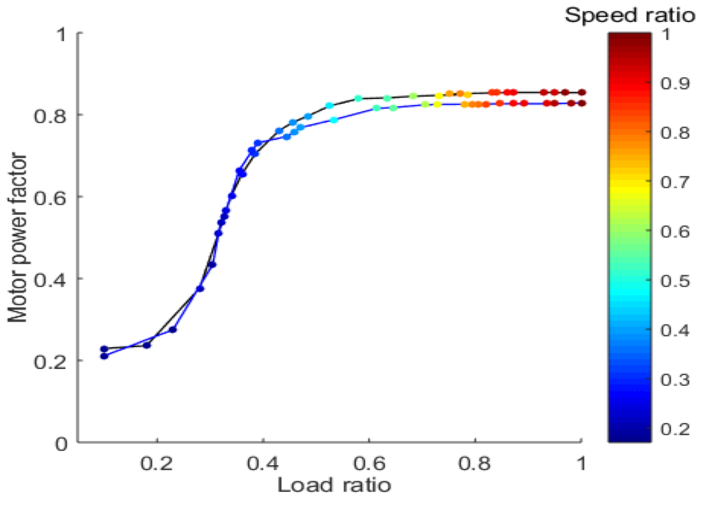

Fig. 10 Relationship between the motor power factor and load ratio at different speed ratios.

The plot of distortion loss ratio (DLR) against the load ratio at a variable speed ratio calculated using Equation (4) is represented in Figure 11. From Figure 11, it can be observed that DLR was increased from 7% to 63% by reducing the load ratio from 100% to 10%. Therefore, the distortion losses play a vital role in increasing the overall line losses of the system during partial loading conditions.

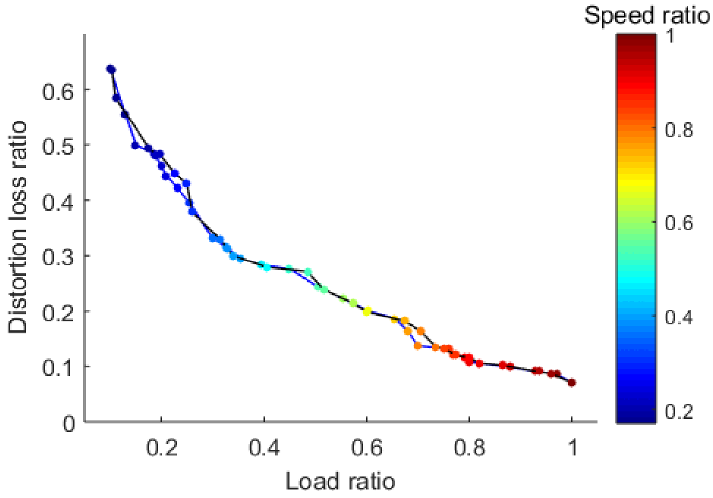

Figure 11. Relationship between the distortion loss ratio and load ratio at different speed ratios.

The variations in the efficiency of VFD fed motors were measured under different loading conditions and speed ratios using Equation (5). The results are shown in Figure 12. From Figure 12, the low efficiency of VFD systems can be observed at minimum load and speed ratios. The variation in the efficiency at smaller values of speed and load ratios is high and vice versa. The relationship between efficiency and load ratio at different speed ratios is useful to determine the optimum operating conditions to obtain better performance. The best possible operation of VFD has been explored in the subsequent section.

It can be seen from the above experimental results that THD_i, temperature, power factor, DLR and the efficiency are insignificantly affected by changing the load ratio from 1 to 0.5 and speed ratio from 1 to 0.55. The effect on these quantities become severe by further reducing the load and speed ratios. The most severe effect on performance parameters is observed when the load ratio is below 0.3 and the speed ratio is below 0.35.

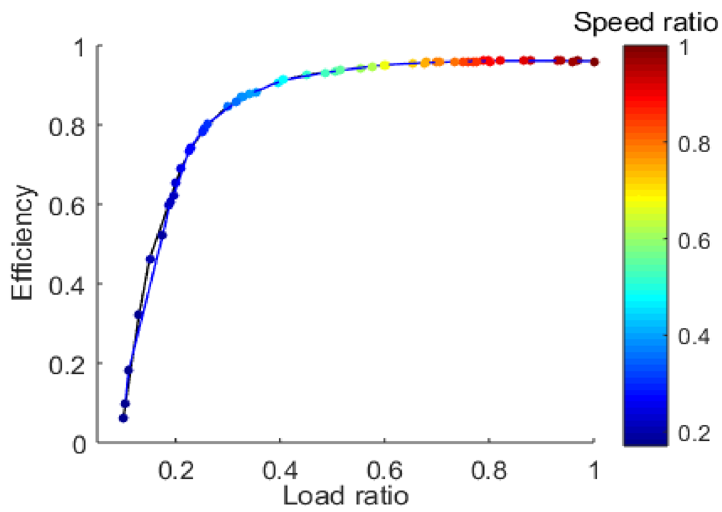

Figure 12. Relationship between efficiency and load ratio of VFD at different speed ratios.

4.3 Relationship Between Performance Parameters and Operating Conditions

Based on experimental findings, the variation in performance parameters with the variations in load ratio and speed ratio can be found through curve fitting. A polynomial relation exists between the performance parameters and the operating conditions. The plausibility of the binomial relationship is established based on the R-square goodness of fit hypothesis. The variation in THDi (z_1) of low voltage VFD fed motors with load ratio (x) and speed ratio (y) is represented by (5).

$$z_1 = -0{,}9426x^2 + 0{,}1562x - 1{,}061y + 1{,}247 + 0{,}7922 \quad (5)$$

Similarly, Equation (6) represents the relation between power factor (z_2) and load ratio (x) at different values of speed ratio (y).

$$z_2 = -2{,}477x^2 - 1{,}67y^2 + 2{,}101x + 0{,}192y + 2{,}702xy + 0{,}01387 \quad (6)$$

The binomial relationship between distortion loss ratio (z_3) of motor fed by VFD, load ratio (x) and speed ratio (y) can be found using (7).

$$z_3 = -7{,}26x^2 - 8{,}623y^2 - 3{,}129x + 1{,}821y + 16{,}64xy + 0{,}6364 \quad (7)$$

Finally, Equation (8) represents the relation between efficiency (z), load ratio (x) at different values of speed ratio (y).

$$z_4 = 30{,}11x^2 + 36{,}79y^2 + 13{,}09x - 9{,}99y - 69{,}48xy + 0{,}406 \quad (8)$$

The performance parameters can be calculated at any value of load ratio and speed ratio using these binomial relations. The mathematical model for the prediction of the efficiency at variable load and speed ratio was already developed in [18]. The forecasted values of both proposed and existing models were plotted against the actual efficiency measured at variable load and speed ratios, as shown in Figure 13.

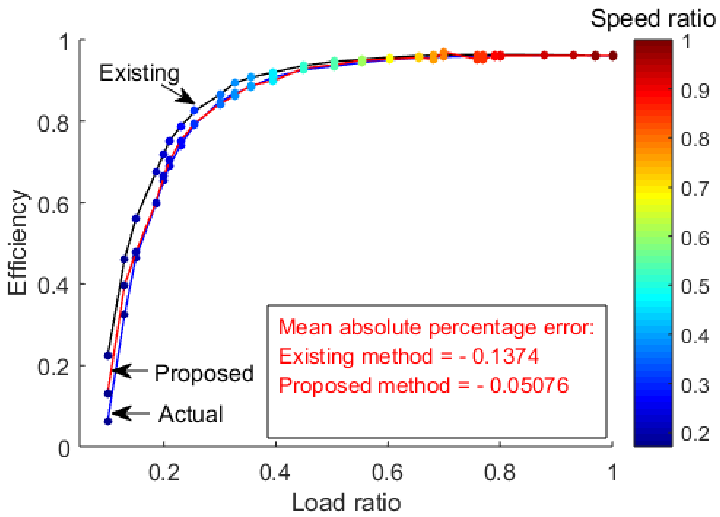

Figure 13. The plot of efficiencies predicted by both proposed and existing models against the actual efficiency measured at variable operating conditions.

Further, the forecasted efficiencies *(P_t)* of both models were compared with the actual efficiency *(A_t)* measured during the experiments and mean absolute percentage error (MAPE) calculated for using Equation 9. The 63% reduction in the MAPE using the proposed model was obtained.

$$E = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{A_t - P_t}{A_t}\right| \qquad (9)$$

4.4 Optimum Operating Conditions

It has been investigated in the previous sections that the performance of the HVAC chiller system is affected by the load and speed ratios. If we focus on the plots showing relationships between the operating conditions and the performance parameters, the optimum operating conditions can be determined. It has been observed that the best and the worst operating conditions are when the load ratio of the VFD system is greater than 0.8 and less than 0.3 respectively. In the best-operating conditions, the performance parameters are insignificantly affected by load variations. The operation of VFD fed motors between 0.8 to 0.3 of the load ratios affects the performance parameters but still, the situation is better than operating these drives below 0.3 of load ratio. Thus, proper design and implementation of operational logic can make this system more efficient under variable load and speed conditions. For the efficient operation of the HVAC chiller system shown in Figure 3, operational logic has been proposed and validated based on the experiments to control all the eight sets of motors fed by VFD installed in four modules of the chiller system.

Consider that the module full load capacity (MFL) of all the four modules and the set full load capacity (SFL) for all the eight (compressor and VFD) sets are equal. Module load ratio (MLR) and set load ratio (SLR) depend upon the load requirements. For achieving better performance, it has been desired to operate this system at maximum load ratio and avoid its operation below 30% of its loading. When the system is

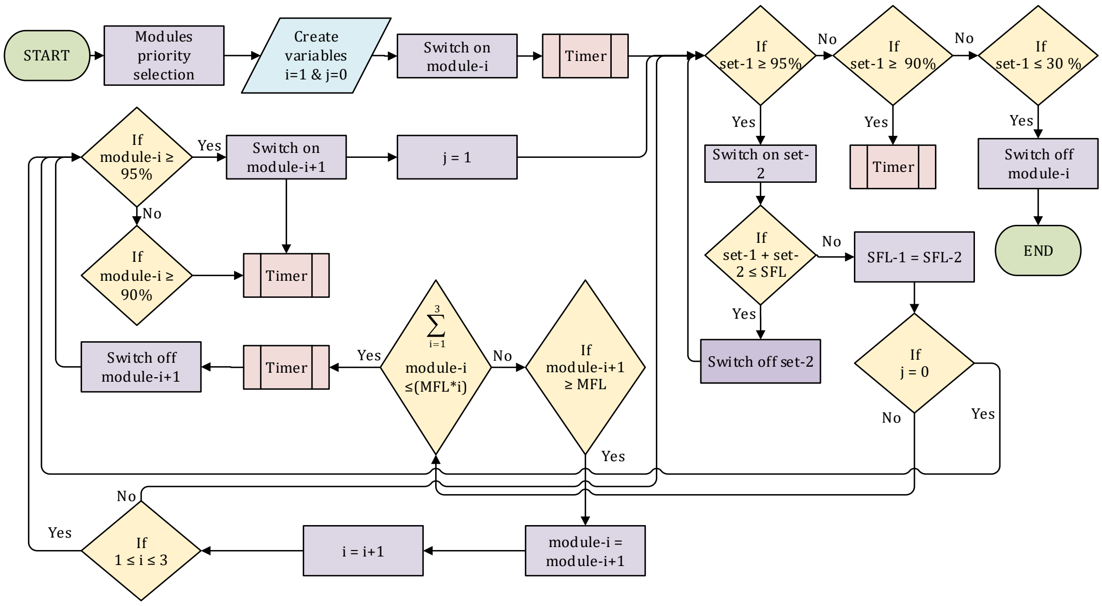

Figure 14. Flowchart representing the best-operating conditions based on experimental results.

energized, the priority of the modules is selected to energize the desired module at first, second, third and fourth priority. For the priority module, one set has been powered on and its load has been increased. When the percentage loading of this set has been reached up to 90%, then a command has been generated to energize the other set in the same module through an adjustable timer. There is also a possibility of an abrupt rise in the load. If the percentage loading of the first set is increased up to 95% before the adjusted time delay then the second set will be energized without waiting for the timer operation.

The severity of the poor performance of VFD increased when it is operated below 30% of loading. Therefore, if the load on the first set is insufficient and even below 30%, the system will be powered off automatically. Every set and module in the system are operated at the maximum percentage loading and switching of the next module or set is dependent on the percentage loading of the sets or modules already energized. If the combined loading of the two sets is less than 100%, then they are operating in underload conditions. For example, if the percentage loading of the two sets is 60% and 30%, then the best operating condition will be achieved when one set is switched off and others take up the complete load requirement of 90% loading. In another situation, if the percentage loadings of the two sets are 70% and 40%, then it is better to operate both sets at equal loading (55%) to achieve better performance at higher values of percentage loading of both sets. This proposed logic was implemented in the HVAC chiller system and improvement in the performance parameters was observed, a detail discussion is in a later section. Based on the experiments, the flowchart shown in Figure 14 for the best possible operation has been designed, implemented and validated.

4.5 Combined Measurements – Existing and Proposed Operating Conditions

The performance of the HVAC chiller system was monitored under both existing and optimum operating conditions proposed in the previous section. The HVAC system was operated in automatic mode for 15 hours under both existing and proposed operating conditions. The measurements were carried out after a specific time interval at two VFD systems to compare the performance parameters under both operating conditions.

In Figure 15, the variation in THD_i of two VFD systems under existing and proposed operating conditions is presented. The average THD_i for the observed time duration under existing and proposed operating conditions are 0.451 and 0.146 respectively. The THD_i of the system is decreased to 67.62% by implementing the proposed operating conditions.

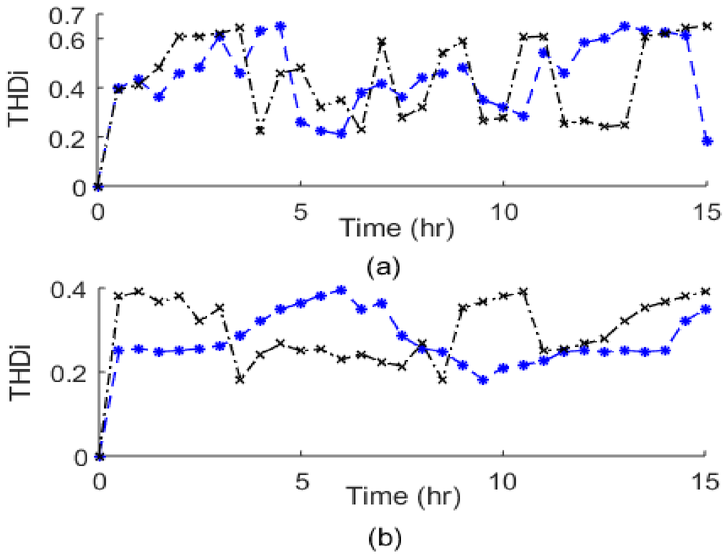

Figure 15. The THDi of both VFD fed motors under (a) existing operating conditions and (b) proposed optimum operating conditions.

Figure 16 shows the variation in the power factor of two motors fed by VFD under both operating conditions. The average values of power factor in the observed time duration for existing and proposed operating conditions are 0.644 and 0.8303 respectively. The power factor of the system is improved by up to 28.9%.

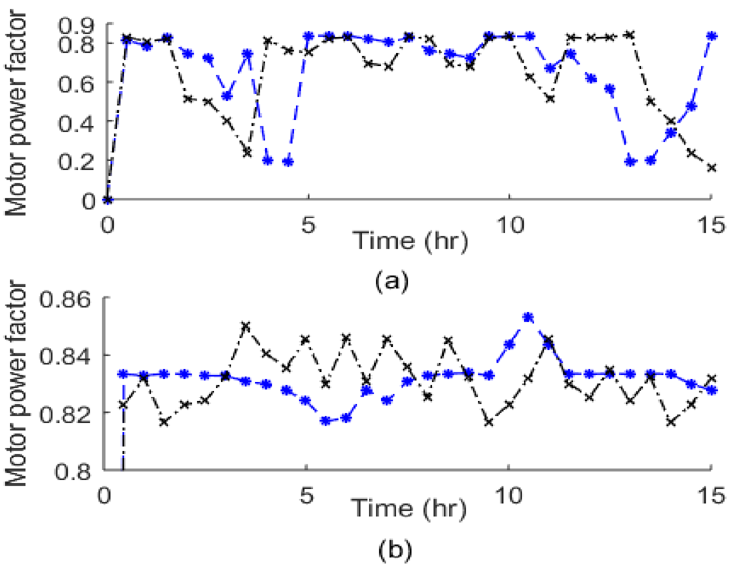

Figure 16. The power factor of both motors fed by VFD under (a) existing operating conditions and (b) proposed optimum operating conditions.

Figure 17 represents the distortion loss ratios (DLR) of two VFD systems under both operating conditions. The average values of DLR for the observed time duration during existing and proposed operating conditions are 0.3224 and 0.146 respectively. The DLRs of the chiller system is reduced to 54.7%.

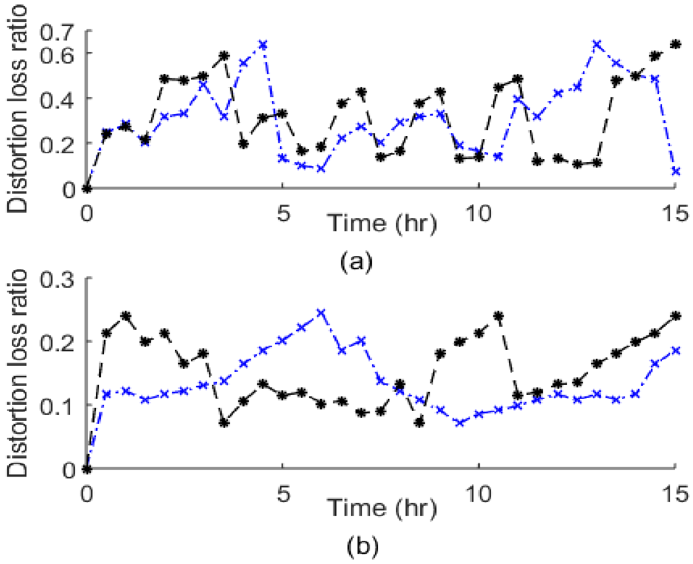

Figure 17. The distortion loss ratios of both VFD fed motors under (a) existing operating conditions and (b) proposed optimum operating conditions.

Figure 18 represents the efficiencies of both VFD fed motors under existing and proposed operating conditions. The average efficiencies for the observed time duration during existing and proposed operating conditions are 0.7672 and 0.9559 respectively. The efficiency of the system is improved to 24.6% by implementing the optimum operating conditions.

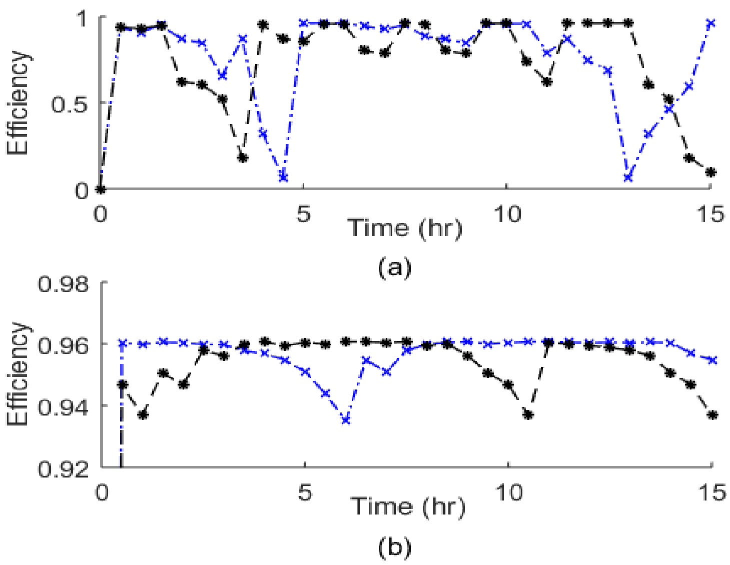

Figure 18. The efficiencies of both VFD fed motors under (a) existing operating conditions and (b) proposed optimum operating conditions.

The average values of these performance parameters of the VFD system under existing and proposed optimum operating conditions are given in Table 2. From Table 2, it can be seen that significant improvement in the performance parameters is observed by controlling the load and speed ratios.

Table 2. The average values of performance parameters under existing and proposed optimum operating conditions and their percentage improvement in the performance.

Parameters	Existing operating conditions	Proposed operating conditions	Percentage improvement
THD_i	0.451	0.146	67.62
Power factor	0.644	0.8303	28.9
Distortion loss ratio	0.3224	0.146	54.71
Efficiency	0.7672	0.9559	24.6

The economic analysis of the HVAC chiller system was made under both existing and proposed optimum operating conditions to estimate the annual net cost benefits. The HVAC system was operated in automatic mode for 60 hours under both operating conditions. The energy consumption after every 10 min during the observation period was recorded and results are shown in Figure 19. From Figure 19, it was observed that the energy consumed by the HVAC chiller system during the proposed optimum operating conditions is 1779.7 units less than the energy consumed during the existing operating condition. By considering the commercial energy unit rate (0.174 $) in Pakistan and expending the energy consumption for a complete year, the total annual cost benefits of 50291 $ can be achieved by implementing the proposed optimum operating condition.

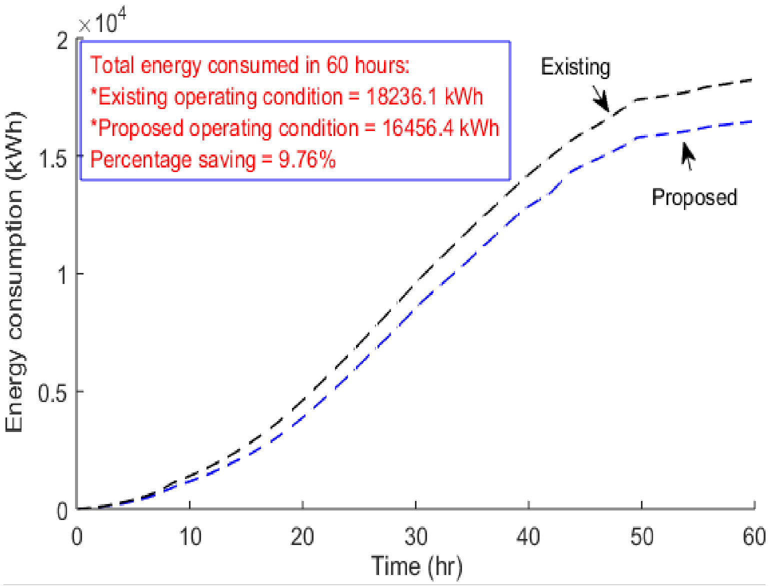

Figure 19. The energy consumed by the HVAC chiller system for 60 hours of operation under both the existing and the proposed optimum operating conditions.

5 CONCLUSION

This paper has discussed the impact of variable load and speed on the performance of low voltage motors powered by VFD, installed in the HVAC chiller system. The chiller systems containing 12 pulse VFD, the 5th and 7th harmonic components play a vital role in improving total harmonic distortion (THD). It has been further demonstrated that load and speed variations in motor fed by VFD have a severe impact on the performance of the chiller system. The performance of the chiller system is insignificantly affected when VFD systems are operated above 50% of the full loading and 55% of the full speed. The impact on the performance of the chiller system becomes more severe when the load on the VFD system is below 30% of the full load and speed of the motor fed by VFD is below 35% of the full speed

Based on the experiments, the relationships between performance parameters and operating conditions were determined through curve fitting. The plausibility of these binomial relations was established using the R-square goodness of fit hypothesis. Further, recommendations were given for the efficient and healthy operation of VFD systems. An optimum operational logic was formulated and experiments were repeated after implementing the proposed operational logic. The results were compared to observe the improvement in the performance of the VFD system. The implementation of the proposed operating conditions in HVAC chiller system was carried out and the efficiency of the system was increased up to 24.6%, THD_i was reduced up to 67.62%, the power factor of motors fed by VFD was improved up to 28.9% and distortion loss ratio was reduced up to 54.71%.

The prediction of the performance parameters of the VFD system at variable speed and load ratios can be made by performing the statistical analysis of data and implementing the machine learning techniques. A comprehensive study to investigate the effect variable operating conditions on degradation of insulation in low voltage VFD and the effect of the harmonic component on partial discharges measurement is recommended for future work.

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