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CASE STUDY ON THE CAUSE OF DRIVE FAILURE IN AN INDUSTRY

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ABSTRACT

KEC Int. Pvt. Ltd. is a Tower manufacturing company, one of its factories is located in Butibori, Nagpur, Maharashtra, India. Machines like cranes are used in manufacturing process like moving workloads quickly and safely, one such operation of the crane is galvanizing steel bars. A Variable frequency drives (VFD) acts as a motor controller for the crane to perform various movements, VFDs provide the intelligence, performance, flexibility and safety for crane applications. With continuous usage the drives are prone to failures; common reasons why drives fail include module failure, power outages and bad network connections. Drives failure issues can also cause from overheating, moisture and electromagnetic interference. One of such failure occurred during the process of galvanizing steel bars, the VFD lost its ability to signal the motor to perform the hoisting movement. In this Case Study we will see how the factory engineers dealt with this systemic issue; inspected the system to ensure these problems do not spiral out of hand, repaired the fault and provided an effective solution by implementing an air-cooling mechanism to the VFD panel.

Keywords: Case Study, Variable Frequency Drive, Drive Failure, Galvanizing, Air-Cooling Mechanism.

I. INTRODUCTION

The industrial revolution has put the use complex machinery in variety of diverse applications to do heavy duty work that manpower cannot. Crane control have significantly advanced in the field of technology in the past few years. Ward Leonard system's contribution to DC drive technology and the debut of powerful Insulated Gate Bipolar Transistors in the 90s introduced the AC drive for motor control. In this paper we will discuss about the case study on a particular type of drive failure that happened while using heavy machinery in an industry during work operation. The Case Study is based upon a heavy-duty crane in KEC International Ltd. which ceased to operate due to Variable Frequency Drive failure, thus the process of detection of the issue, repairing it and finding an effective solution is explained.

KEC International Private Limited, India, is an Engineering, Procurement, and Construction company. The Tower Manufacturing Facility of KEC, Butibori, Nagpur, Maharashtra, India, is managed independently and are one of the largest factories in the field of manufacturing towers in Maharashtra. In addition to this, the capability of catering to tower wise bundling requirement of the customer to enable storage and easy supply of tower to desired locations. For this, there is an in-house developed special purpose horizontal cum vertical bending press for bending the different section sizes and capable of catering to zinc coat thickness in the range of 65 to 130 microns as per customer requirement, this process of coating steel bars to prevent it from corrosion is called galvanizing. Heavy duty cranes are used to move the steel bars across different tanks used in the process of galvanizing, the 5.5kW, 10.9A, 945 RPM motor on the crane is controlled by a 5.5kW, 14.6A VFD Controller. To make sure that at the rated speed of the driven equipment is unhinged, the nominal ratings of the VFD should be the same as those of the motor. This is why in our case, both the VFD and the crane's motor is of 5.5kW.

1.1 Basics about VFD:

A Variable Frequency Drive also known as VFD acts as a controller to an electric motor by changing the frequency and voltage supplied to the motor. The other names for a VFD are variable speed drive, adjustable speed/frequency drive, Microdrive, AC drive and inverter. In VFDs, frequency is directly related to the motor's speed which means, faster the frequency, faster the RPMs will go. If an application does not require an electric motor to run at full speed, the VFD can be used to ramp down the frequency and voltage as per the requirements of the electric motor's load. Whenever the application's motor speed is required to change, the VFD can simply turn up or down the motor speed to meet the speed requirement. Usually, the AC electric motor used in a VFD system is a three-phase induction motor.

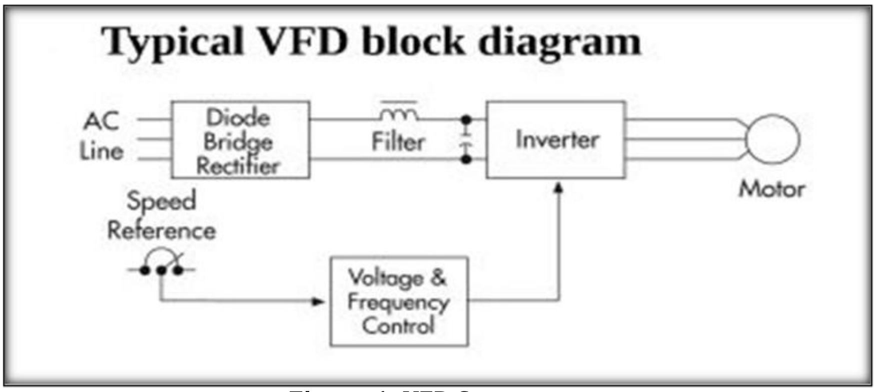


Figure 1: VFD System

If the VFD is located close to corrosive agents like salt, water for example, can be a very nasty agent and it will easily attack insulation wirings if we do not have them tropicalized. If the VFD does not have heating winding resistances, the agents will attack windings insulation thus increasing the temperature from within and causing failure. This reason is the main cause of failure of the VFD in KEC. Int. and the one our Case Study is based upon, this happened during the process of galvanizing steel bars needed for Tower manufacturing.

Figure 2: The IB – 55 grade VFD panel on the heavy duty "Electromech" crane.

II. ANALYSIS OF THE CASE STUDY

To find out the root cause of drive failure that happen in the company, a brief explanation about the process of galvanization is needed.

2.1 Process of Galvanization:

Galvanization is a manufacturing process where zinc coating applied to steel or iron materials to protect and prevent it from rusting. There are many galvanizing processes available, but the most commonly offered and used method is called the hot-dip galvanizing (HDG), one of such HGD plant is there in our industry. The HDG plant is big enough and has 4 tanks for degreasing, and molten zinc. The work was done to learn about the different techniques and quality check. After the HDG process is finished, quality check is done, the final product is then sent to the storage and further to sites according to the client's orders, during this process the failure happened in our case. The process is as follows:

- The steel bars are cleaned in a degreasing solution.
- After being cleaned, the steel bars are pickled by being lowered into a tank of diluted hot sulfuric acid, this is done in a hot Galva furnace tank.
- The steel bars are then fluxed in an aqueous solution of chemical additives like zinc-ammonium chloride.
- The steel bars are then galvanized through immersion in a tank of molten zinc.
- Afterwards, the steel bars are inspected for consistency and a complete coating.

2.2 Cause of Failure:

During the process of galvanizing steel bars, the crane has to lower the bars into four tanks using the hoisting movement. Heavy duty cranes have high initial torque hence they are used to lift heavy loads. The Variable Frequency Drive is programmed to instruct the motor of the crane to perform the hoisting, cross travel and long travel motion for heavy duty cranes. The crane couldn't perform the hoisting movement but was able to perform the other two types of movements, hence it was clear that the VFD was malfunctioning. After a close inspection it was found out that one of the IGBT inside the VFD got shot circuited because of the settlement of moisture on it causing it to overheat.

The main cause of drive failure is found out to be because of the fumes that emerge from the Galva tanks when the crane lowers the bars inside the tank, the fumes move up towards the VFD panel, from there it enters the drives and settle there, creating a layer of moisture over the drive and causing the drive to overheat and short circuit.

Figure 3: Toxic fumes emerging from the tank and going towards the VFD panel.

The immediate action as per the guidelines was to cease the operation of the crane, safely move the steel bars away from the tanks to a distant area and allow it to cool down. The workers were then advised to use water hose pipe to splurge water onto the bars so as to remove the residual chemicals and the after the cleansing air fans were placed around the bars to dry out.

2.2 Inspecting the Fault:

Figure 4: VFD Showing the "oh" fault error.

An oH1 (Overheat Fault) occurs when the heatsink temperature of the VFD reaches the overheat fault level which is typically 5° C to 10° C. Failure Mode and Effects Analysis (FMEA) was used to determine the potential failure modes for VFD and its effects on the operation, from the FMEA's analysis, either the IGBT or the motor stator winding were identified as the components with high susceptibility to failure. From the analysis, failure effects from gate unit supply were very severe it resulted in uncontrolled voltage and frequency from the inverter and consequently resulting in degraded operations of the pump motor. In the similar fashion, failure of the DC link which is responsible to store constant DC energy for inverter use can be catastrophic, this could be due to the failure of capacitor leading to IGBT's failure to produce the desired sinewave. The failure of Inverter, in particular the IGBT has significant effect on the overall reliability of the VFD and on the crane's motor as well. From FEMA, it was observed that the rise time of VFD PWM pulse had a major impact on the peak voltage at the motor's terminal and this peak voltage overshoots results in insulation breakdown and subsequently can cause stator coil damage as well, therefore, it indicates IGBT's fault.

Test meters have trouble reading VFD output voltage because an AC motor prefers sinusoidal power, but a variable frequency drive's output voltage isn't sinusoidal. A VFD's output voltage is a series square pulses which ranges from wider to thinner to emulate a sinewave. The image shown below shows a typical voltage output from a VFD:

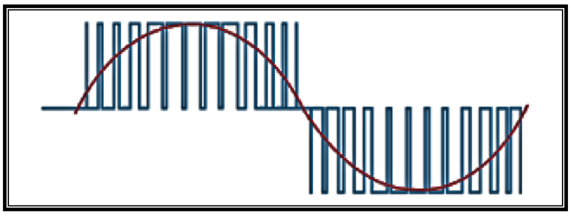
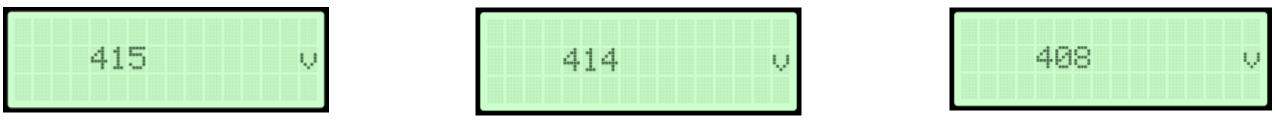


Fig. 5: VFD output voltage

The VFD Voltage Output is one of the factors causing issues and it would help to figure out the fault. The square pulses can cause multimeters to give illogical results as the peak of the pulses is always the same, some of the meters will show little change in voltage as the motor speeds up. The average voltage to the motor increases but the meter reacts mostly to the peak of the pulses. The solution is to use only meters with built-in low-pass filters as these meters can read VFD output voltage properly. Special meters are required to read the that value properly as the motor's strength is a function of the fundamental voltage applied.

It is known that out of balance phase voltage even as little as 1 percent can result in a ten times greater motor current unbalance therefore, the excessive amounts of current flow can quickly cause the motor to overheat. Hence, to figure out the voltage unbalance we have to measure the voltage from phase-to-phase for each of the phases, sum up the three readings and divide it by three. By this we will get the average phase-to-phase voltage. Now from the value, if any of the three individual readings varies by more than 1 percent from the average, we have a voltage unbalance. From the FEMA, at 5 percent voltage unbalance the motor is bound to overheats and destroy. This happens because there are too many single-phase loads being supplied by one individual phase. Thus, these loads must be evenly distributed among phases at the panel board to correct the issue. The voltage drops between VFD and motor terminals should absolutely not exceed 3%, even unbalance greater than 2% is deemed to be problematic.

As seen in the values below, there's a difference in 3rd rating of B-C phase, thus voltage unbalance is a sign of an impending diode failure – a common failure mode for a VFD. It is found out that the voltage unbalance is because of a differing impedance during the conduction angle in a diode string, rather than the incoming voltage unbalance to the VFD from the source.



A-B A-C B-C

Figure. 6: VFD Output Voltage Readings

The unbalanced current can also cause voltage unbalance and makes it difficult to separate the cause from the effect. The problem which arises is the bad heat dissipation. IGBTs and the diodes may get short circuited if they get too hot. This is either caused by the heat shock on the power section or the IGBT drive circuit fault.

2.3 Repairing the VFD:

The IGBTs inside have an antiparallel diode, so it helps with the measurements as well. Basically, one cannot check an IGBT inside the circuit, but what we can check is the antiparallel diode and it tells us a lot. Usually if the IGBT go bad, it goes with the diode as well, so if we cannot measure the diode or we measure short, one gets a bad IGBT as well. We had to disassemble the entire device to measure the power section and the power section of the VFD had to be taken out. Choke and the capacitors are on the top side and on the left the switch mode power supply for the IGBT driver ICs and for the controller board is situated.

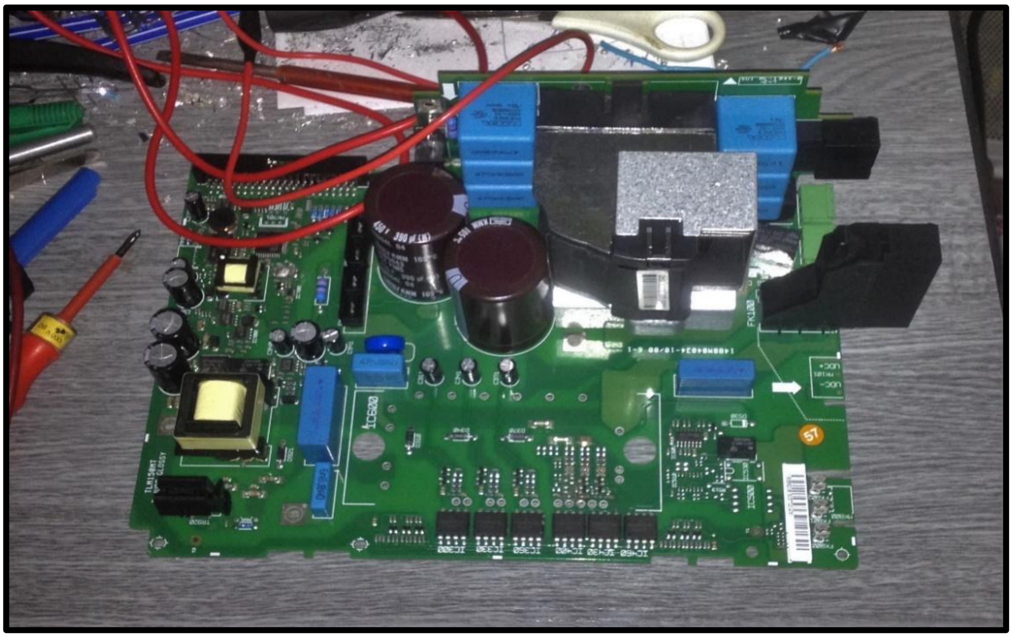


Figure 7: The power section PCB.

We can see it is an integrated power module, which has all the rectifier diodes and all the IGBTs in one package as it is an effective way to save space so the drive can be smaller. These types of modules have some type of silicone that after the damage contains the smoke in it as shown in the figure below. After we found the problem, it was time to replace it with another power module, which can be a substitute. The module is of the Danfoss brand, 415V, 15A rated.

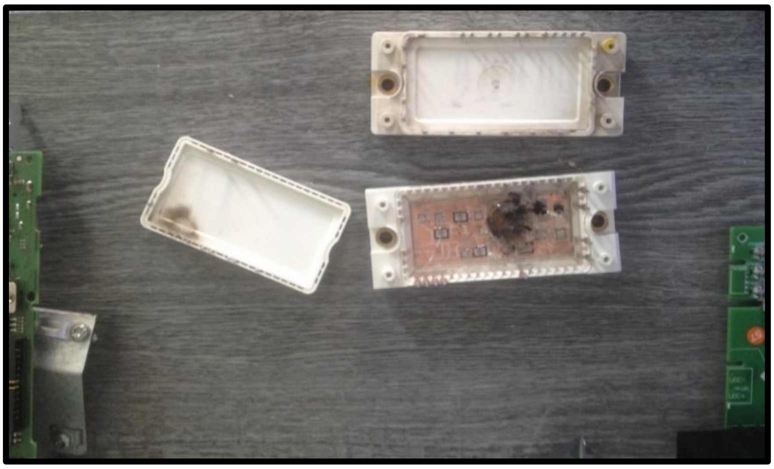


Figure 8: The actual power module was soldered out from the PCB

After this we had to measure all the IGBT drive circuits, because always if the IGBT damaged, the driver circuit is damaged as well, and if we didn't repair this before we test the device, it can get damaged again. For this it is important to know that the driver circuit in most cases is the same on the upper three IGBT driver as well as on the lower three. We compared the parts on each channel with the multimeter to find the faulty components. The drive circuit have some minimal protection, and these are usually blown, these are some Zener diode and the gate resistor on the gate of the IGBT. Sometimes the IGBT driver IC is not damaged, but it's recommended to change in those channels' driver ICs, where the IGBT was blown.

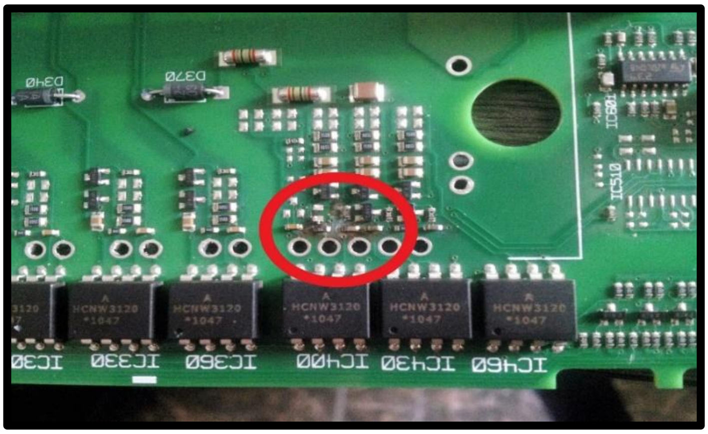


Figure 9: The driver ICs are the HCNW3120 and in the middle we can see some missing parts, those was the blown parts.

Some Zener diode, regular diode and some resistor was damaged in the circuit, so we had to change those. It was important to solder back and repair these before we placed back the power module, because after it is placed, the module covers all of those. After all the capacitors and drivers are checked, we started to reassemble the device. One should be careful and do not miss any steps in the reassembly. For testing after the reassembly, we had a three-phase motor which is fit for the rating of the VFD. It needed to be done carefully, because we never know 100% it would not blow up until the motor is enabled. To lower the risk, we placed three 100W around 4 - 6 Ohm resistor series before each phase input. This gave a little bit of protection from blowing up the device with full power, it creates a current limit, if anything goes short in the drive under test. Everything went well, and the variable frequency drive got functional again.

III. SOLUTION

VFDs are usually housed in enclosures which are designed to protect them from dust, dirt, water, and other external factors. During VFD operation, heat is generated inside of the enclosure thus the cooling-air required must satisfy both of the major components of a VFD which are a computer and a power supply. For computers, optimal operating conditions generally range from a dry-bulb air temperature of 68°F to 75°F and a relative humidity of 45 percent to 55 percent. For VFD power-supply systems, optimal cooling-air temperature is higher. For optimal operational conditions, a VFD enclosure should be maintained at about 75°F and 50-percent, which is in line with general air-conditioning requirements. With this we can say that the average VFD-enclosure's operational air temperature which is the average of the cooling air entering and exiting the enclosure should be 75°F. In our case the fumes generated during the process of galvanizing aggravated the temperature inside the enclosure.

The most reliable and consistent way to cool a VFD enclosure is to apply air cooling. This type of cooling is expected to maintain the enclosure's temperature at normal operational conditions as well as help to prevent the moisture from migrating inside of the enclosure. With this, some reduction in VFD operational efficiency is seen. Because of that, VFD-enclosure cooling air cooling typically is reserved for the most critical applications like the ones that are done in KEC Int. Pvt. Ltd

Air cooling of VFDs have the following advantages:

1. An air-cooled VFD cooling system is self-contained, equipment such as pumps, piping, filters, deionizers or heat exchangers are not needed.
2. The servicing of the client's HVAC system is more quickly done.
3. Smaller VFDs can often be used to control large motors for a short time rating.

3.1 Insight about the work done to cool down the VFD used on the crane in KEC:

When calculating heat load, we engineers consider the components within the control panel. We have to ensure regarding what factors may lead to temperature spikes, or fans, which actively remove heat (albeit that crane operation like in KEC often force dirt and debris into the enclosures they're designed to be cooling). Fans are particularly important, and thus, to determine the amount of heat a fan can remove, the diameter of the fan is considered as it corresponds to a typical air flow volume in CFM (cubic feet per minute) of hot air to be removed. We can consider that to raise the temperature of one pound of water by 1 degree Fahrenheit, 1 BTU/hr. is the amount of heat required, this is also the amount of heat needed to raise or lower the temperature of one cubic foot of air by 1 degree Fahrenheit in one minute. By this we can say that for every CFM the fan is moving, we are reducing the temperature of the air by 1°F. In simple terms, we can remove 1 BTU/hr. for every °F multiplied by every CFM the fan is moving. Therefore, we used a 3-inch fan to remove approximately 22 CFM. Thus, in an VFD enclosure having current temperature differential of approximately 15 °F, this fan is expected to remove approximately 330 BTU/hr.

$$15\,\cancel{°F} \times 22\,\cancel{CFM} \times \frac{1\,Btu/hr}{\cancel{CFM}\,\cancel{°F}} = 330\,Btu/hr$$

Figure 10: Measurement of the diameter of fan installed on the VFD panel.

There will be holes where the fan is installed, should be closed with either sheet metal using rivets, sealant, duct tape or other safe to use methods known as it is important to cover and seal the fan panel. The fan will usually draw in debris like bugs and other stuff, this will eventually form a layer on the electronics and cause the VFD to overheat. A design to filters the air intake will help in this case, this will require routine maintenance to keep the air filter from clogging and casing the fan to fail. The design we are using has the fan blowing on a special kind of metal, transferring the cooling into the electronics, without the dirty air actually having to touch the electronics. Although it will keep the dirty air out of the electronics, the air intake can still be clogged with debris which will eventually overheat the VFD, therefore, proper maintenance is required.

IV. RESULTS AND DISCUSSION

Thus, we learned that VFDs can generate a significant amount of heat in grueling operations like galvanizing, this heat can cause the drives to overheat and trip unless it is removed through the use of enclosure cooling. Thus, to show how effective our solution to the issue was we will calculate the heat generated before and after the implementation of cooling system, before that it needs to be taken into consideration that some of the parameters such as thermal loss in VFD, its efficiency and exact temperature were taken as approximation as it was not possible for us to measure it at the time of failure and during galvanization process. But the approximated values are nominal and are globally approved as well as followed. Thus, now we will calculate only the heat loss happening under **normal circumstances**, during the process of galvanizing the temperature may significantly increase but the cooling system placed by us is still robust enough to maintain an ideal temperature.

- The first thing we'll consider is the **Drive Efficiency:**

The ideal efficiency of most VFDs is usually between 93 to 98 % and the balance of the energy is lost as heat. According to Yaskawa, the manufacturer of our VFD used in KEC, the efficiency is 97% and the heat loss is approximately 3 % for the A1000 model in use.

- Accounting for Other **Losses**:

As we've learned in the previous chapter, the thermal loss seen in VFDs may for all practical purposes be assumed to be about 3%. It can be approximately 4% for smaller VFDs and as the size increases, the percentage of thermal losses decreases to about 3 percent. The thermal losses of ancillary equipment such as DC reactors, phase shifting transformers, power supplies and switch gear are also taken into consideration. In some cases, their values are insignificant, therefore their losses can be outed from the total heat load. In our case it is pretty insignificant as there are not many equipment between the crane motor and drive.

- **Maximum Operating Temperature:**

It is really difficult to determine how much the temperature rises during galvanization operation. The drive manufacturers specify the maximum allowed operating temperature of their VFDs, this value can be relatively low in some cases as it allows for the heating effect of power electronics on to the different circuit boards inside the VFDs. Yasakawa in particular mentioned we can take the drive's temperatures above 104 ºF.

- **The Total Heat Load:**

The heat load of the VFD enclosure is determined by adding the total sum of heat dissipation of all items in operation. It is important to note that the calculation needs to take into account the heat transfer through the cabinet walls as a result of the ambient temperature and local heat sources. There are various ways this can be calculated but the most effective method is to use the standard formulae, the estimated heat generated by a Variable Frequency Drive controlling a motor at full load is-

$H_{loss} = P_t (1 - \eta_d)$

Where,
H_{loss} = heat loss to the variable-frequency drive surroundings (kW)
P_t = electrical power through the variable-frequency drive (kW)
η_d = variable-frequency drive efficiency

Thus,
H_{loss} = 5.5 kW (1 – 97/100)
H_{loss} = 0.165 kW

Now as a solution we placed a 3" fan which under normal operating temperature of 15 degree Celsius is estimated to remove 330 BTU/hr.
1 W is equal to 3.41 BTU/h. Therefore, to convert BTU/h into Watts we have to divide it by 3.41.

Therefore,
330 BTU/hr / 3.41 = 96.77W = **0.096 kW**

Subtracting it from the heat loss happening under ideal condition,
0.165 – 0.096 = **0.068 kW**, is the heat loss happening after implementation of Air-cooling mechanism.

Thus, 330 BTU/hr is more than sufficient to control the temperature of the VFD under normal circumstances. With this we gained the assurance that during the process of galvanizing the 3" fan is enough to remove the heat and maintain tranquility even when temperature level rises significantly during galvanization process.

V. CONCLUSION

KEC International Pvt. Ltd. manufactures parts needed to build towers; manufacturing steel bars comes under the due process. Here, a heavy duty "Electromech" crane is used to lift the steel bars and move it across four tanks to carry out the process of galvanizing steel bars. The VFD controls the motor performing hoisting movement to place the bars into the tanks. It was during this procedure a failure occurred which ultimately led to the shutdown of manufacturing process. The reason was that the toxic fumes that emerged from the H2SO4 tank got to the VFD panel and increased the enclosure's temperature, the VFD's fault alarm stated blaring, on the screen it showed the "oh1" fault which means that the VFD's temperature has reached the threshold limit and some components are severely damaged, therefore, the motor was unable to hoist the bars. We engineers then had to manually lift the bars from the tank and clean the steel bars carefully. After further inspection it was found that the increase in temperature was the direct cause of the VFD failure and the crane's motor lost the ability to hoist the steel bars, the power module and the IGBT on the PCB of power section got blown. The power module was irreparable so it had to be replaced, the IGBT circuit was repaired my manually measuring each and every Zener diodes, regular diodes and resistors to determine which of them got damaged.

After the VFD got repaired it was time to provide an effective solution so that failures like this don't occur in the near future, The solution to this issue was to implement a cooling fan panel on the VFD, for an effective cooling we had to select an appropriate size for the fan as the diameter of the fan corresponds to a typical air flow volume in CFM (cubic feet per minute) within the enclosure. As per the calculations, we used a 3″ fan to bring down the heat generated / power loss to 0.068kW from 0.165kW under ideal VFD operation, although its temperature is bound to increase during the process of galvanizing, with the results we got from the calculation, we can safely assume that the temperature will remain under nominal range. It was not possible to monitor the actual temperature during the process of galvanizing due to the hazardous nature of the process.

Thus, the chances of failure of the VFD during the process of galvanizing got significantly lowered and no such incidents occurred after the implementation of air-cooling system. In conclusion, this paper helped us explain about the case study we did on the failure of VFD controlling crane motor during the process of galvanizing helped us deeply understand the functionality of VFDs, with that we also understood how to analyze the cause of the failure and the process to repair the fault. We implemented a proper, cost effective cooling mechanism so that failure like this doesn't happen often and cause hindrance to the production work of the company.

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