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Harmonic Mitigation in Economical Way: A Case Study.

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Harmonics is the reality today in every facility. There are many myths and confusion about the right way to mitigate harmonics in the power distribution system. Harmonics mitigation is a challenge and it becomes more complicated with an operating facility having a power distribution system with an automatic power factor correction system (APFC Panel). This case study evaluates various options that any facility's management will have for an economical yet effective harmonic mitigation option. It is a case study in actual application at a small manufacturing facility in Tamil Nadu. The requirement was mandatory to meet the TANGEDCO (Tamil Nadu Generation & Distribution Corporation Ltd.) set harmonics target to avoid the penalty. A step-by-step approach was taken to study the existing situation, analyze the data, and weigh the pros and cons of various options to select an option to meet the requirements. The study outcome proved convincingly that for any operating facility having an automatic power factor correction system, the best option is to first convert the existing system into a de-tuned passive harmonic filter in situ and then evaluate further for necessary corrective actions, if any, for further harmonic mitigation plans. It is not only cost-effective but also convenient as it does not affect the ongoing operations of the facility, be it manufacturing or commercial.

Keywords: Harmonics Mitigation, Tuned Passive Harmonic Filter, De-tuned Passive Harmonic Filter, Automatic Power Factor Correction System, Active Harmonic Filter, Power Factor.

1. Introduction

Traditionally electrical power distribution system design was with an automatic power factor correction system using a power capacitor to compensate the reactive power losses so that the actual power factor can be maintained very close to unity(21). It was needed because the load was mainly inductive type and the machine control system was straightforward and without much use of semiconductor components (11). Over time and as technology developed the usage of semiconductor components in the machine control circuit increased which led to the uneven current drawn resulting in harmonics generation. An increase in harmonics in the distribution system will have many cascading effects which will also increase the risk in the facility's operations (2). Due to this practical operational problem, the consultants started designing the power distribution system with de-tuned passive harmonic filters instead of an automatic power factor correction system. The main

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difference between the two is the addition of reactors into the system which will act like a blocking circuit for the harmonic current. Therefore, the combined effects of the capacitor and reactor will not only compensate for the reactive power loss but also block the harmonic current to some extent (7). And this is the current practice in India across the industries.

The systems supplied and installed in the last 15 years are de-tuned passive harmonic filters. However, the systems supplied before that were automatic power factor correction systems. Harmonic audits across the industries, whether new or old, show a higher level of harmonics current. Every facility has 3rd, 5th, and 7th-order harmonic present over the prescribed limit mainly due to the lighting load, battery charger, receptacle mount loads, UPS, VFD, etc. which are common loads in every facility (9). The facilities having the power factor correction systems are more affected due to higher harmonics current. In the meantime, some of the state's distribution companies introduced new policies to maintain a certain limit of voltage and current harmonics instead of power factor. Failing to do so leads to a huge penalty. TANGEDCO (Tamil Nadu Generation & Distribution Corporation Ltd.)is one such state organization where maintaining harmonic current became the new norm. It was done under the direction of a tariff order by the Tamil Nadu Electricity Regulatory Commission (TNERC), wherein any HT consumer/generatorneeds to meet the specified harmonic limits as per norms stipulated in CEA (Central Electricity Authority) regulation on grid code (12, 13).

These facilities had options like replacing the existing system with a suitably designed active or tuned passive harmonic filter, replace with a de-tuned passive harmonic filter, or converting the existing system into a de-tuned harmonic filter and then deciding the further actions. This paper evaluates these options through a case study in an actual application. Harmonics are present in every facility due to the non-linear nature of loads and cause huge problems for the safety and security of equipment and data. Mitigation of harmonics is a need of the hour and many state Governments are seriously planning to implement penalties for not maintaining a prescribed level of harmonics in their respective facilities in the industry (17).

Harmonics is a matter of concern for both TANGEDCO and the industries as it affects both. The bottom line is that it affects performances. Industries are concerned because it causes unnecessary hindrances in operations due to equipment failure and data loss (30). TANGEDCO is concerned because it affects their ability to provide clean and adequate power to their customers. Harmonics mitigation is the way forward to overcome these problems both on TANGEDCOs and the industry's part. It is always better to mitigate the harmonics at the machine level that generates the harmonics. Alternatively, it can also be mitigated at the Point of Common Coupling (PCC) (23).

The presence of harmonics in electricity distribution companies not only increases distribution losses in the system but also decreases the life of electrical equipment. Malfunctioning of circuit breakers and relays, overheating of conductors and cables, and premature failure of transformers, motors do have a root cause as harmonics in most cases (5). If harmonics in the system are beyond a limit, the reliability of the electrical system also decreases. All the above effects of harmonics have an impact on the overall operation of consumer and distribution companies.

2. Harmonic MitigationOptions

There is a general perception among the industries that mitigation of harmonics is a capital-intensive project (19). It becomes more complicated in an operating facility when it goes for expansion and modernization. Fly-by-night operators are always there to create confusion in the customer's mind for their petty gains. Some ill-informed professionals also tend to create hurdles when the customers look for information to make a decision. There is always a better way to mitigate harmonics because it is not one pill-for-all solution but a tailor-made solution (4). This case study highlights one such specific case where the solution was not only technically feasible but also commercially viable. Depending upon the severity of harmonics, the type of harmonics, and the objective of the consumer, there are several solutions available in the market that can meet the requirements. Each solution has its benefits and limitations. Various harmonic mitigation techniques that are available can be listed below (31). Few technologies need to be adopted at the design stage whereas few technologies can be implemented as a retrofit or additional component/equipment.

- Line Reactors.
- Isolation Transformers.
- Tuned Passive Harmonic Filters.
- De-tunedPassiveHarmonic Filters.
- Active Harmonic Filters

As mentioned, each solution has its advantages and limitations. There is no single solution that is better than other solutions. A careful and detailed study of the harmonics in the system along with consumer requirements can result in the selection of the best possible solution (24). The selected solution could be either one or a combination of the few technologies mentioned above.The section below shows a brief about each technology and its application.

Line Reactors

Line reactors are one of the simplest and lowest-cost technologies for the mitigation of harmonics. These are used at the load end and in line with the load that is generating harmonics. Line reactors are very common with variable frequency drives. They operate on the principle of increasing the impedance of the circuit. If a plant has a 1000 kVA transformer with an impedance of 7% and a drive of 100 kVA. This drive will have an approximate impedance of only 0.7%. As the transformer impedance will be very small relative to each load, a line reactor in series will improve the impedance of the circuit (32).One of the major advantages of a line reactor is its lowest cost and reduction in harmonic levels to a greater extent. Another advantage is that since they are installed right at the load end, harmonic distortion is reduced in the distribution system (29). One of the limitationsof installing a reactor on the power distribution system is the increase in the total percentage reactance of the circuit which will decrease the power factor leading to a poorer regulation.

Isolation Transformer

The isolation transformer is one of the very effective means of not only mitigating harmonics but also other power quality issues like transients, common mode noise, and zero sequence currents. The operating principle of an isolation transformer is also based on a line reactor, which increases system impedance (34). The leakage inductance of isolation transformers increases circuit impedance so that harmonics are reduced to a great extent. Typically, a delta–wye configuration is used in isolation transformers. Since, the primary is delta connected and the secondary is wye configuration, zero sequence currents (Triplen harmonics) will not transfer to the primary side of the network (8).Due to capacitive coupling between winding and shield with proper grounding, transients, common mode noise, and zero sequence currents are not reflected on the other side of the transformer. Isolation transformer has the added advantage of eliminating other power quality issues in addition to harmonics over line reactors. Their harmonic mitigation capability is the same as that of a line reactor but can be very useful where zero sequence currents and other power quality issues as mentioned above are present (38). Their cost of being around 5 -6 times higher as compared to line reactors.

Tuned Passive Harmonic Filter

Tuned harmonic filters are a combination of capacitors and reactors (inductors) which are connected in series to form a tuned circuit. This tuned filter is connected in parallel to the main system. As the LC circuit is tuned to a particular frequency to form resonance, it offers the lowest impedance to that particular frequency (harmonic). Harmonic current instead of flowing to the utility, flows through the filter being low impedance path.A tuned Harmonic Filter is specific to a particular harmonic frequency(22).

De-Tuned Passive Harmonic Filter

This is like a general-purpose harmonic filter and not particular to any order of frequency. Low pass filters or de-tuned filters can attenuate all order of harmonic frequencies. De-tuned harmonic filters are a combination of series and shunt elements of reactors and capacitors.The shunt circuit prevents the attraction of harmonics from other sources where are series circuits filters of primarily 5^{th} and 7^{th} order harmonic. They are one of the most economical means of mitigating harmonics (33).

Active Harmonic Filter

Active harmonic filters are the latest among all technologies for the mitigation of harmonics. They continuously monitor the load current along with the fundamental and harmonic current. Based on the order of harmonics and their magnitude, Active Harmonic Filter will detect, generate, and inject an equivalent magnitude of individual harmonics with a phase shift of 180 degrees (14). These injected currents will nullify the harmonics in the system. Active harmonic filters can filter out harmonics up to the 50^{th} order of harmonics. So Active Harmonic Filters need some energy to drive themselves. As active filters use fast-switching IGBTs, they produce noise while switching which can cause disturbances in the system. These noise signals can also be harmful to the sensitive equipment. The presence of high voltage distortion can also affect the performance of active harmonic filters. In terms of cost, they are the costliest among all available options (41).Apart from the above technologies, some other techniques apply the principle of de-rating where equipment is capable of handling harmonics. One of the examples is K-rated transformers which de-rates a transformer to withstand higher temperatures generated due to harmonics.

3. Methodology

A step-by-step approach (10) is adopted since it is a case study in real-life applications in an operating manufacturing plant. The existing system is an automatic power factor correction (APFC Panel) system as a standard power distribution practice in the industry. The plant operating procedures and needs are understood by a plant visit to ensure a smooth and non-interruptive action plan (20). The power quality and harmonics readings are measured and recorded for an hour with normal plant operating conditions so that the same can be compared against the readings taken after converting the existing system into a de-tuned passive harmonic filter. A list is prepared for the components to be replaced to convert the existing system. A new wiring diagram is prepared to ensure the correct workmanship with the replaced and new components in the system. All materials are procured and the new wiring is made as per the renewed wiring diagram. On the agreed day the existing system is isolated and disconnected from the bus-bar so that the conversion work can be done without any risk. The additional components like reactors are fitted inside the panel, and replacement components like higher voltage-rated capacitors and contactors are replaced. Additional exhaust fans are fitted on the panel for better heat extraction. After the new components are fitted the new wiring is replaced with the old one. Once the system conversion is done in situ a visual check is done to ensure everything is secured properly and it is safe to do further tests (42). Cold checks and insulation checks are done before connecting the new system which is a de-tuned passive harmonic filter back to the power distribution system. Power quality and harmonics readings are again measured and recorded for an hour with normal plant operating conditions. This reading is compared with the earlier readings to decide whether there is any improvement in power quality and reduction in harmonics content in the distribution system (28).

4. Plant Power Distribution System

The case study is done in one of the leading leather shoe manufacturing plants in Tamil Nadu. The plant receives power at 11kV which is stepped down to 440 volts. The base demand of the plant is 320 kVA where as the contract demand was 400 kVA. The average registered demand during the last 12 months is around 328 kVA.The rated capacity of the transformer is 500 kVA. The power distribution schematic is illustrated in Figure 1.

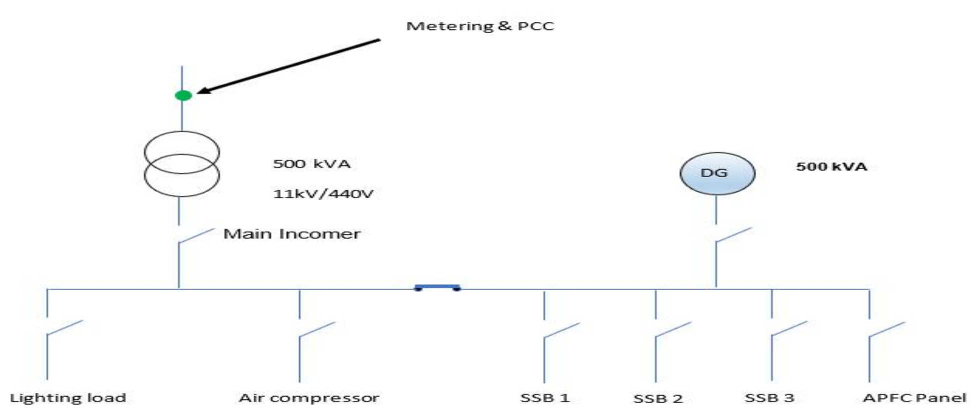

Figure 1: Single Line Diagram of Power Distribution System

Loads in the plant constitute mainly motors with drives. VFDs or drives are non-linear loads that generate harmonics and can get circulated into the power distribution system, if not controlled, being a closed-loop system (15). TANGEDCO carries out routine measurements at the consumer incomer being the Point of Common Coupling (PCC) and if harmonics are found to be high, the consumer is asked to reduce the harmonics within a given time.

The shoe manufacturing plant also got a notice from TANGEDCO asking them to reduce the harmonics below the specified limit. The specified limit of current harmonics is 8% and voltage harmonics is 5% by TANGEDCO. All HT consumers must keep current and voltage harmonics as specified by the TANGEDCO. Based on the notice, the shoe manufacturing plant carried out a detailed harmonic study of the plant for further necessary actions.

5. Harmonic Study Summary

A detailed harmonic study is carried out in the plant by a contractor specializing in harmonic mitigation. During the study, harmonics are measured at different nodes in the plant at the following locations.

- Main incomer
- SSB – 1
- SSB – 2
- SSB – 3
- Lighting load
- Air Compressors

The harmonics readings at the main incomer node are discussed here since TANGEDCO will monitor the same at this point.

Main Incomer (PCC)

At the main incomer being the PCC, measurements are taken with the system in "ON" condition and "OFF" condition. Graphs in Figures 2&3 show current waveforms at the main incomer when capacitors are "ON" and "OFF" respectively. The voltage waveform is not shown because the readings are insignificant and within the limit.

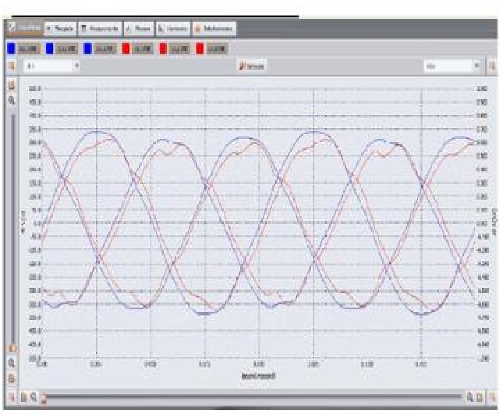

Figure 2: ON

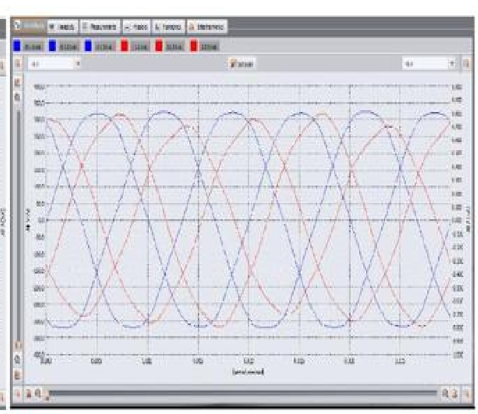

Figure 3: OFF

It can be seen from the waveform that the current waveform is distorted when capacitors arein “ON”condition.Figures4&5showthe individual order of harmonics with capacitors “ON” and “OFF” condition.

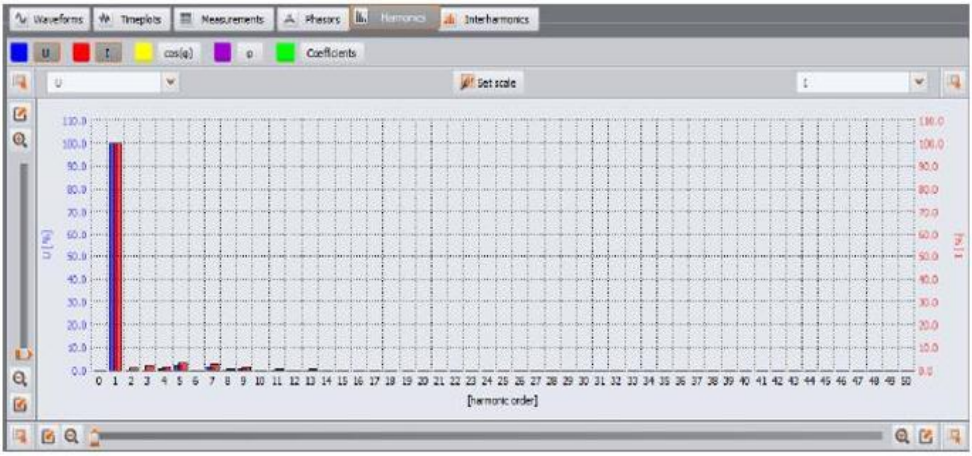

Figure4: Individual Order of harmonics when capacitors are ON

Figure5: Individual Order of harmonics when capacitors are OFF

As seen from the above graphs when capacitors are in “ON” condition, the % THD voltage and current are 3.28% and 13.53% respectively. When the capacitors are in “OFF” condition, the % THD voltage and current values are 2.44% and 3.48% respectively. Predominant harmonics are 5^{Th} and 7^{Th}.

The above measurements indicate that significant current harmonics are not generated by the load but are amplified due to capacitor banks. The plant could not isolate capacitor banks while capacitor banks were in “OFF” condition, the power factor dropped to 0.79 from0.98 which would result in higher maximum demand by the plant and a possible PF penalty. Table 1 shows a summary of measurements at other locations in the plant.

Table1: Summary of harmonic measurement

Location	Capacitor	Voltage (V)	Current (Amp)	% THDv	% THDi	P F	kVA	Harmonic current Amperes
Main incomer	ON	404.3	404	3.28	13.53	0.98	255.22	54.66
	OFF	405.2	496.1	2.44	3.48	0.79	334.99	17.26
SSB 1		410.6	257.3	3.61	6.41	0.75	175.19	16.49
SSB 2		391.6	34.75	4.32	13.48	0.81	19.18	4.68
SSB 3		421.2	46.63	4.69	9.08	0.74	26.17	4.23
Compressor 1		431.5	60.07	5.86	11.92	0.82	41.99	7.16
Compressor 2		430.7	59.91	4.75	10.24	0.82	43.29	6.13
Lighting Load		402.7	79.53	4.23	29.49	0.73	40.96	23.45
UPS		417.5	14.79	4.58	135.41	0.56	9.53	20.03

As seen from Table 1, the total harmonic distortion current at the main incomer is 13.53% which is more than the limit specified by TANGEDCO. Measurements at different load centers also show a higher % of THDi which is more than 8%. In terms of harmonic current, major contributors are lighting load (29.49%), UPS (135.41%), compressors (11.92% & 10.24%), and SSB-2 (13.48%).Based on the harmonic measurement study, the plant management needed to mitigate harmonics.

Selection of Solution

After carrying out a harmonic study and based on the outcome, the plant team decided to mitigate harmonics. The next challenge for the plant team was to select a technology that would be technically suitable and financially feasible. The plant team had mainly three options available for the mitigation of harmonics. These three available options are:

- Active Harmonic Filter.
- New Passive Tuned Harmonic Filter
- De-tuned Harmonic Filter(Convert the existing APFC into a de-tuned filter in situ).

The plant team compared the above three technologies based on technical feasibility, harmonic mitigation capability, ease of operation, maintenance cost, operating cost, and initial cost.Table 2 shows a comparison summary of the above technologies.

Table 2: Comparison of various technologies

Technology	Active harmonic filter	Passive harmonic filter	De-Tuned harmonic filter
Technically feasible	YES	YES	YES
Harmonic mitigation capability	Up to 50th order of harmonics	5th, 7th 11th and 13th	5th, 7th 11th and 13th
Ease of operation	Very Easy	Very Easy	Very Easy
Maintenance cost	High in case of any failure	Low - LC Circuit	Low - LC Circuit
Operating cost	High - Power consumption of IGBT's	Negligible	Negligible
Initial cost.	800,000	400,000	200,000

The harmonic spectrum of the plant consisted of mainly 3rd, 5th, and 7th order harmonics as predominant harmonics. Other harmonics present in the system were 11th and 13th.Based on the above comparison, the plant team opted for the third option and decided to convert the existing APFC system intoa detuned harmonic filter of 100 KVAR capacity in situ.

Post Implementation Results

After converting the existing APFC system in situ and making it a de-tuned passive harmonic filter, the plant team carried out harmonic measurements at the incomer. Figure 6 shows the current waveform after the installation of the detuned filter.Figure 7 shows individual harmonic order.

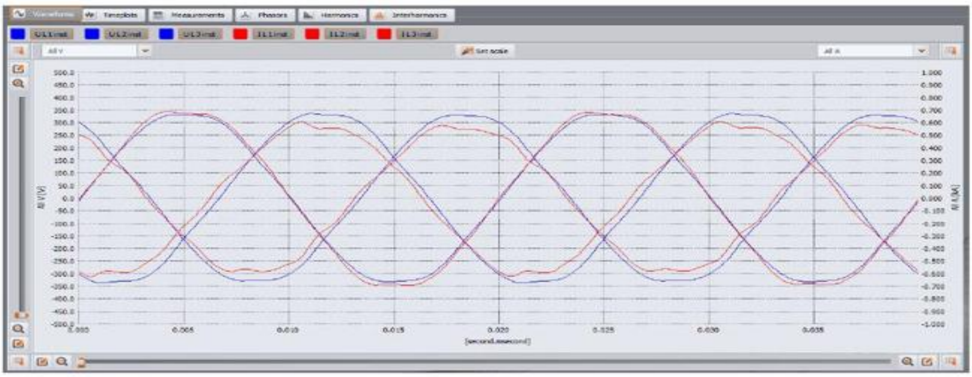

Figure 6:Current waveform after installation of detuned filter

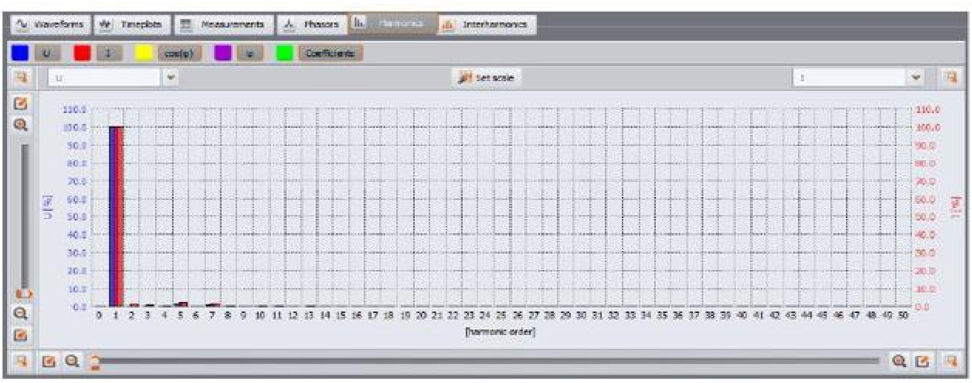

Figure 7: Individual orders of harmonics

Table 3 shows the summary of the mitigation result.

Table 3: Summary of the Result

Location	Voltage	Current Ampere	% THDv	% THDi	PF	kVA	Harmonic current Amperes
Main incomer	419	531.5	2.4	4.69	1.00	347.89	24.93

As seen from the table, after the installation of the detuned harmonic filter, the total percentage current harmonic distortion has come down to 4.69% from 13.53% which is well below the limit specified by TANGEDCO.

6. Conclusion

The plant management had 3 options to choose from. These are (i) active harmonic filter in addition to the existing automatic power factor correction system, (ii) replacing the existing automatic power factor correction system with anew tuned passive harmonic filter, and (iii) converting the existing automatic power factor correction system into a de-tuned passive harmonic filter in situ and then decide further course of actions if needed. The first option would cost Rs. 8,00,000, the second option would cost Rs. 4,00,000, and the third option would cost Rs. 2,00,000. The plant management decided to first explore the third option. Post-conversion of the existing automatic power factor correction system into a de-tuned passive harmonic filter and further harmonic readings with the normal operating condition resulted in a satisfactory level of harmonic which was within the IEEE limit (43) and at the same time a very desirable level of power factor as shown in Table 3. The highlight of the performance is the reduction of current harmonic to 4.69% from 13.53% while the power factor is 1. The third option is not only cost-effective but also meets the requirements of the plant management without any compromise with the day-to-day operations.

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