Energy Efficiency Improvement by Introducing Variable Frequency Drives for the Tea Withering Process

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Abstract

Tea is a key export revenue source of Sri Lanka. It is a large energy consuming sector. The highest energy consuming operation in the tea manufacturing process is withering of tea leaves. The Energy NAMA project implemented by Sri Lanka Sustainable Energy Authority with the assistance of the United Nations Development Programme, introduced Variable Frequency Drives (VFDs) to replace damper control of tea withering fan motors and a few other applications.

The concept of using VFDs was first introduced in year 1999. This project identified reasons for the low interest shown by tea factories to use VFDs for the withering process, addressed issues/barriers, provided financial support for procurement and installation of VFDs, conducted training of staff on effective use of VFDs and monitored energy savings. This project installed 555 VFDs in 71 tea factories. The operational data of these VFDs were monitored and verified at the end of the project.

It was observed that energy saved with VFDs for airflow control of withering troughs is significant in most cases. This paper presents the technical approach to the VFD program and results obtained. Results indicate an energy saving between 12% and 32% if VFDs are introduced along with optimum operating practices.

Keywords: withering, variable frequency drive, energy

Introduction

Sri Lanka is the world's fourth largest tea manufacturer [1] and the third largest tea exporter [2]. The total income from tea exports in 2018 was US\$ 942.2 million [2]. Tea exports accounted for about 14% of total exports and about 62% of total agricultural exports [3].

The tea industry is a major consumer of electrical and thermal energy. It requires almost 235 GWh of electricity per year. This is about 7% of the total electricity consumption in the country [4].

Electricity is used mainly to drive machines and a small fraction is used for lighting. In the case of orthodox tea production, the withering and rolling processes consume more energy compared with other stages of the process [5]. On the average, withering uses between 35% – 50% of the total electricity requirement of a tea factory [6]. Figure 1 shows the energy consumption of different sub-processes or equipment in an orthodox tea factory in the low grown region and that of a factory in the high-grown region.

Figure 1: Energy Consumption of Two Tea Factories

Source: Energy Audit Reports of Nivithigala Tea Factory and Wanarajah Tea Factory, 2013.

Variable Frequency Drives (VFDs) were first introduced in 1999 for tea withering applications in Sri Lanka by the Energy Conservation Fund (presently Sustainable Energy Authority or SLSEA) with the assistance of Sri Lanka Tea Research Institute (TRI) [7].

There are 719 tea factories [11] listed under the Sri Lanka Tea Board. About 747 factories are in active operations, including some factories not listed by the Tea Board. Only a few factories have installed VFDs on withering fan motors. As withering is the most energy consuming process of tea manufacture, energy efficiency improvements for this process could lead to significant savings in the factory energy requirement.

Tea Manufacturing Process

There are two primary processing methods to produce black tea: The orthodox method and the cut, tear, curl (CTC) method.

Manufacturing commences when tea leaves are picked or 'plucked'. Plucking calls for discrimination and dexterity. Only the uppermost foliage on every stem is picked. On arrival at the factory, the raw leaf is weighed. After weighing, tea leaves are laid out for withering. The withered leaf is then sent for rolling. Rolling is a mechanized process in which the leaf twists and breaks to release the natural juices. This action activates enzymes that help to initiate fermentation. Rolling also gives the leaves a curled appearance.

To bring out specific intensities in flavours, the amount of oxidation the leaves undergo need to be controlled. Controlled-oxidation is typically carried out in a large room where the temperature is maintained at 25-30° C and humidity is maintained at 60-70%. Rolled leaves are spread out on long shelves and left to ferment for a fixed period. The duration depends on the type of tea being made. The tea after the fermentation stage is now called 'dhool'.

To maintain the tea to be moisture-free, it is dried after the fermenting process. To dry the fermented dhool, tea leaves are fired or roasted at a low temperature for a controlled period inside an industrial-scale dryer. Drying enhances the flavour and ensures a longer shelf-life. The moisture content of tea after drying is between 2% to 3%, and the coppery brown fermented tea particles will change to black colour.

The fired tea is cooled and graded/sifted according to size and shape. The sifting is carried out on a series of grading and cleaning machines. These comprise several trays of different mesh sizes for separating tea particles to various grades of tea and to remove the stalk and fibre. On completion of the grading, teas are stored in airtight bins or boxes.

There are two major differences between CTC and orthodox tea manufacturing. (i) In orthodox tea manufacturing, the quantity of moisture removed from the green leaf during wither is higher, compared with CTC manufacturing. (ii) The CTC process uses cutters to curl, twist, and

cut withered tea leaves instead of rollers used in the orthodox method.

Figure 2: Schematic of Orthodox Tea Manufacturing Process

Withering

Withering is the most important step in the process of manufacturing black tea. The partial removal of moisture in fresh tea leaves, making the leaves flaccid and pliable, and preparing the leaves for further processing, is called withering. This is done by blowing air through the tea leaves spread on a bed known as the "withering trough". The withering process is shown in Figure 3. A fan blows air to remove moisture in tea leaves laid on the trough. Air leaves the trough carrying the moisture. These fans are driven by electric motors of capacities ranging from 3 kW to 11 kW. The size of motor depends on the length of the trough, type of the fan, and other parameters. A withering cycle has a duration of about 12– 18 hours. The duration depends on ambient conditions and the condition of the leaf.

Figure 3: Schematic Representation of a Tea withering trough

In open troughs, leaves are spread to a particular thickness. Air is blown in an upward direction

from the bottom to the top layers. This way, the bottom layer of the leaves will become withered sooner than the upper layers. At certain intervals during the wither, leaves are manually turned upside down, so that all the leaves get evenly withered.

Withering is carried out at temperatures between 20°C and 30°C, depending on climatic conditions. A difference of 4 – 6°C between wet bulb and dry bulb temperatures is maintained by mixing ambient cold air with hot air from, received from the factory furnace or from an external heat source.

Trough fans usually deliver 20 m³ of air per minute at a water gauge pressure of 13 mm for each kilo gram of green leaf [7].

During the withering process, it is very important to control the flow rate, humidity and temperature of air flow over time. During the initial stage of withering, surface moisture on leaves evaporates faster and the moisture removal rate becomes slower in subsequent stages. This is because in latter stages, determines the [8]. More than 50% of moisture removal takes place during the first 4 hours of the withering cycle. Hence, the amount of air supplied for withering could be regulated according to the moisture removal rate [9]. The leaves are loosely spread at the beginning of the wither but get densely packed over time. It is necessary to turn the leaves at least twice during the withering cycle in addition to periodic loosening to ensure even withering.

The normal practice is to operate the withering fan at full speed throughout the process. Air flow is controlled by restricting the air inlets to the fan using manually operated dampers (). These mechanical methods do not save significant amount of energy, although the airflow is reduced.

Figure 4: Conventional Methods of Controlling Air Flow to a Withering trough

Variable Frequency Drives

VFD is an electronic motor controller that drives and varies the speed of an electric motor by varying the frequency and voltage supplied to the motor. A VFD can control the speed of a fan motor to regulate air delivery to meet a specific requirement. Therefore, it is a more appropriate to control the air requirement for withering. Electrical energy used by the fan motor varies with the motor speed. Therefore, there will be a saving of electrical energy at lower fan speeds.

According to affinity laws, power required to drive a fan is inversely proportional to the cube of the fan speed. A graphical representation of affinity laws is shown in Figure 5. Reducing speed by half will cause the power consumption to reduce by one eighth.

When the air flow is reduced from 100% to 80% the power input drops from 100% to 51%. When the flow is reduced from 100% to 50% the power will drop from 100% to 12.5%.

Figure 5: Graphical Representation of Affinity Laws

VFDs in Tea Withering

Several studies were conducted to estimate the energy saving potential using VFDs to drive withering fan motors. One study was conducted in St Coombs Tea Factory, Thalawakelle. Two identical troughs of similar dimensions and motors were selected, one as the test trough and the other as the control (reference) trough. They were loaded with the same quantity of green leaf of similar quality at the same time. Green leaves received from the field were spread at uniform density in selected troughs, and fan motors of both troughs were started after loosening the leaves. Physical parameters of inlet air were maintained at the same level. As shown in Figure

6, the airflow of the test trough was controlled using a VFD, based on observations and instructions of the factory staff. The other control trough was allowed to follow the conventional method of flow control using dampers. Electrical and operational parameters were monitored in the test trough and the control trough. In addition, the set frequency of the VFD was also recorded. Initial weight and moisture content of green leaves, final weight and moisture content of withered leaves were recorded. The moisture content of the leaves was also recorded at regular intervals.

Figure 6: VFD Test Arrangement

Figure 7 shows the variation of motor power consumption with and without the VFD. It was observed that 41% of the electrical energy used for withering could be saved by close monitoring and controlling airflow using VFDs. The required wither was obtained within the usual time period and there was no difference in the quality of the product.

The main parameter that affects the energy saving potential is the operator's behaviour. The operator is expected to ensure that the required airflow is delivered by regulating the VFD. The other important aspects of the process are loosening and turning of the leaves at required time intervals while maintaining a correct hygrometer difference. The physical condition of the trough structure, fresh air dampers, hot air dampers, material and the design of fans have an impact on the actual energy saving potential. With an energy saving potential of around 30% - 40%, the application of VFDs for tea withering is a financially feasible investment with a simple payback period between 3 to 4 years. The energy saving potential will be significant if wider application of VFDs could be achieved. Thus, the Energy NAMA project decided to encourage interested tea factories to install VFDs for withering trough fans, providing technical and financial assistance.

Figure 7: Variation of Motor Power Consumption with VFD and without

Without VFD: 60.2 kWh
With VFD: 35.4 kWh

Project Intervention

Although the technology has the potential to save energy in the withering process it was not yet popular in the industry. The Energy NAMA project proposed to provide financial support to tea factories interested in introducing VFDs. This was launched as a pilot program. The main aim of the program was to popularise the technology and demonstrate the energy saving potential.

As detailed in Table 1, the program assisted over 70 tea factories with a financial subsidy to install 555 VFDs under a strict quality control process. A comprehensive training was provided to the factory management and operators on the effective use of VFDs for the withering process.

Estimation and Monitoring of Energy Savings

Energy savings were systematically accounted through a web-based energy management portal developed by the project. Only two parameters are needed to estimate energy savings during a pre-defined period. According to the technical specifications provided, all the installed VFDs should be equipped with an inbuilt timer and an energy meter. Timers provide cumulative operating hours (actual motor running hours) and the energy meters provide the cumulative energy flow through the VFD. These two parameters could be easily read by the operator and used for energy calculations.

Table 1: Details of VFDs Installed in Tea Factories

Growing Region	Ownership	Manufacturing Method	Number of	
			Factories	VFDs
High	Regional Plantation Companies (RPCs)	Orthodox	37	273
		CTC	2	20
Mid	RPCs	Orthodox	7	59
		CTC	3	28
	Private	Orthodox	1	4
		CTC	1	5
Low	RPCs	Orthodox	4	34
		CTC	1	10
	Private	Orthodox	14	122
		CTC	0	0
Total			70	555

The monthly energy saving is given by.

Energy Saving = Baseline consumption - Project Consumption ----- (1)

The baseline energy consumption is the energy consumption of a particular trough fan motor if it operates without the VFD during the period considered.

For the calculations it was assumed that the motor operates at full speed for 50% of the total withering period. This value will be less than 50% for a properly controlled and closely monitored system.

The difference between $kW_{@50Hz}$ rating of an installed VFD energy meter and the original power consumption of the motor were measured using a separate instrument. This was tested in a few locations and a 2% uncertainty was observed.

The impact of reducing inlet air flow using mechanical methods, on the energy consumption of the fan motor was also tested with a selected sample. However, a regular pattern was not observed for this. Hence, to make the energy saving estimation more conservative, a 5% reduction of $kW_{@50Hz}$ was considered for all the VFDs.

Baseline Consumption = {Energy consumption when dampers are fully open + Energy consumption with dampers partially closed}

Energy consumption during 1st half of withering = $\{1.02 \times kW_{@50Hz} \times (H_2 - H_1) \times 0.5\}$ ---- (2)

Energy consumption during 1st half of withering = $\{1.02 \times kW_{@50Hz} \times (H_2 - H_1) \times 0.95 \times 0.5\}$ ---(3)

Baseline consumption = $\{[1.02 \times kW_{@50Hz} \times (H_2 - H_1) \times 0.5] + [1.02 \times kW_{@50Hz} \times (H_2 - H_1) \times 0.95 \times 0.5]\}$

= $1.02 \times kW_{@50Hz} \times (H_2 - H_1) \times 0.5 \times 1.95$ ----- (4)

where,

$kW_{@50Hz}$: Power consumption of the fan motor operating at rated speed with fully open air inlets of a loaded withering trough (kW)

H_1 : Motor running hour counter reading during the previous month (hours)

H_2 : Motor running hour counter reading during the present month (hours)

Project consumption is the actual amount of energy used by the withering fan motor during the monitoring period.

Project Consumption = $[(kWh_2 - kWh_1)/0.97]$ ----- (5)

where,

kWh_1 : Energy meter reading during previous month (kWh)

kWh_2 : Energy meter reading during the current month (kWh)

VFD efficiency: 97% (assumed common to all makes and models).

Observations and Results

Operating details of all 555 VFDs were collected and analysed to estimate the cumulative energy saving. Data for VFDs with a saving percentage above 5% (for both CTC and orthodox factories) and below 45% (only for orthodox factories) were included in the detailed analysis. Details of 446 units were considered. Energy savings would have recorded below 5% owing to errors in reading baseline motor power consumption ($kW_{@50Hz}$) or not controlling VFDs. Savings achieved by close monitoring and control by the project team was around 40% and hence saving below 5% can be due to reading errors.

Total energy saving and the percentage energy saving through each VFD was calculated for each factory. The factory average percentage savings were calculated by considering the energy saving of VFDs in each factory, excluding readings that fall outside the range given above.

Figure 8 shows the percentage energy savings recorded by CTC tea manufacturing facilities during November 2019. The energy saving potential was between 21% and 56%. A higher energy saving percentage was observed in these factories.

Figure 8: Percentage Energy Savings by CTC Tea Factories

Figure 9 and 10 show the average of the percentage energy saving recorded by high grown, mid grown and low grown orthodox tea manufacturing facilities by end of November 2019. All the high grown factories are owned by RPCs, while in the other two regions, there were both RPC factories as well as privately owned (PVT) factories.

Figure 9: Energy Saving in High-Grown and Mid-Grown Orthodox Tea Factories

Average energy savings of 45 high and mid grown orthodox tea factories is shown in Figure 9. The percentage energy saving has an average of 22.1% with a median of 20.3% and a standard deviation of 9.7%. Factory numbers 22 and 27 in Figure 9 have recorded a comparatively higher savings as they have installed VFDs only for high energy consuming motors of 7.5 kW and 11 kW capacity.

Figure 10: Histogram of Energy Savings by High-Grown and Mid-Grown, Orthodox Tea Factories

According to Figure 10, data fits into a normal distribution. A total of 190 VFDs out of 280 in high and mid-grown areas have demonstrated an efficiency improvement of 12 - 32%.

Figure 11: Energy Savings by Low Grown, Orthodox Tea Factories

Figure 11 shows average energy saving recorded by 17 low-grown orthodox tea factories while the distribution of the recorded percentage energy saving of 106 VFDs within these factories. The energy saving percentage from low-grown orthodox tea factories have an average of 17.0%, with a median of 16.3% and a standard deviation of 7.8%. 72 out of 106 VFDs demonstrated an efficiency improvement of between 9% and 25%.

Discussion and Future work

Out of a total of 555 only 502 VFDs installed in the tea withering troughs were considered for the analysis. This was due to erroneous results received for other VFDs.

Figure 12: Histogram of Energy Savings by Low-Grown, Orthodox Tea Factories

Withering time was the same for both VFD and manual airflow control. The energy consumption after installing the VFD cannot increase unless it operates the motors at a speed higher than the rated speed. Readings on 42 VFDs indicated no energy savings. Energy savings of 72 units were below 5%. Incorrect power consumption readings at the baseline condition could lead to a negative reading because the maximum speed was set to the rated speed of the VFDs. These need to be reanalysed and corrected in the future.

CTC Tea Factories: The amount of moisture removed from green tea leaves is less in the CTC tea manufacturing process. Hence, CTC factories can use VFDs to either reduce the airflow from the beginning of the withering cycle or to maintain a comparatively lower airflow after a few hours from the start.

Energy savings in low country tea factories are comparatively lower. The recorded energy saving potential in low-grown tea factories was comparatively lower than that of mid and high-grown tea factories. Low-grown tea factories mostly use tea leaves sourced from small-scale tea growers. They receive green leaves in the evening and the withering starts in the evening. Rolling will be carried out in the following morning. There will be no controlling of the airflow during the night. VFDs are used only in the morning to maintain a low airflow after achieving the required wither.

This project conducted training programs to educate factory executives, operators, and technicians in almost all the partnering factories. However, frequent changes of trained persons was identified as one barrier for successful implementation. However, there is a requirement to educate the senior management on the

effective use of VFDs, and the senior management should provide proper instructions and guidelines to the factory staff, ensuring effective use of VFDs.

Monitoring of operating parameters and reporting of data was in a very poor. Even after providing training and a web-based application for monitoring of energy saving, these activities were poorly carried out by the staff members. The same situation has been reported 20 years ago [10]. The tea sector has systematic data collection, recording and reporting mechanisms. Therefore, the industry should be able to record these without much effort if the senior management is keen in knowing the actual benefits achieved.

The project successfully implemented an online monitoring application for two tea factories. The status of each VFD could be remotely monitored and it has the capacity to store operational information through a mobile device or a computer.

In the final stage of the program, tea factories were supported to install VFDs for other suitable applications such as dryer fans, boiler/furnace induced draft (ID) and forced draft (FD) fans. Few factories benefitted from this initiative as only 35 VFDs were installed in 12 factories. Most of these VFDs could be automated although the VFDs used for withering cannot be automated since it requires hand feel for quality. Specially the automation of boiler/furnace ID, FD fans lead to substantial fuel saving in addition to the electricity savings.

Most commonly available trough fan-motors are 4 kW, 5.5 kW and 7.5 kW. Given below is a cost benefit analysis for the installation of VFDs of these capacities.

Table 2: Cost-Benefit Analysis of VFD Applications for Tea Withering

Description	4 kW	5.5 kW	7.5 kW
Average operating at 16 hours/day for 250 days (hours/year)	4,000	4,000	4,000
Average annual power consumption without VFD kWh/year	12,800	17,600	24,000
Saving potential with 25% saving / (kWh/year)	3,200	4,400	6,000
Cost saving at unit cost 15.00/kWh / (LKR/year)	48,000	66,000	90,000
Average investment (LKR)	185,000	245,000	260,000
Simple payback period (years)	3.8	3.7	2.9

Costs considered here are for VFDs with a higher ingress protection ratio (IP54) and included surge protection devices. Hence, these units will serve more than 10 years with proper maintenance as compared to the low IP rated units installed without lightning protection. Further to this the energy costs could also be reduced, if a few VFDs are installed in the same factory. Only the direct savings of electricity was considered in this study and other indirect benefits have not been considered. Maintenance costs of VFDs were not included in the above calculations. Beneficiaries of the program also claimed that there is an improvement in the product quality and reduction in the quantity of refused tea.

Tea factories that have their own tea estates receive green tea leaves in the afternoon and most of these leaves have gone through the initial withering by 6.30 pm. Hence these factories can enjoy an additional cost saving by operating trough fans at a lower speed during peak hours (6.30 pm to 10.30 pm) during when electricity is more expensive.

Proper production planning techniques should be used with the VFDs. Leaves in all the troughs should be ready one after the other for smooth operation in rolling, drying and sifting processes. Factory staff can control withering to meet this schedule by proper control of airflow using VFDs. This can eliminate machines and labor idling in the factory.

The program assistance covered approximately 10% of tea factories in Sri Lanka. Many of the remaining factories have not fixed VFDs for withering troughs. Some other applications in tea manufacturing and in other industries, too, have

opportunities to introduce VFDs as a measure of improving electrical energy efficiency. Hence any attractive business proposal by potential service providers themselves or partnering with financial institutions, will be able to attract those industries with potential.

Despite the financial support and awareness about the benefits, there has been a very poor interest shown by tea factories towards this initiative. Some of the observations made in this regard could be summarized as follows.

- Factories have other issues that should be addressed as a priority.
- Although there is focus on addressing the concerns is on plantation aspects there is less attention to carry out energy efficiency improvements in the manufacturing process.
- Conventional manufacturing methods are preferred over the modern methods.
- Reluctance to work with electronic equipment, mainly due to inadequate qualified and trained technical staff
- Lack of confidence in the electricity savings because of this initiative.

Conclusion

The introduction of VFDs for tea withering fan motors has a potential to save energy and reduce the cost of production while improving the product quality. However, proper control of VFDs by operators is essential to achieve energy efficiency improvement and they must be trained to use the VFDs instead of conventional methods.

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