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Energy saving analysis of air fan motor in power plant boiler controlled by variable frequency drive

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ABSTRACT

A reporting of Energy Audit in 2018 by LEMTEK UI has reported that air fan system currently used in Power Plant of PLTU Tanjung Jati B Jepara is inefficient, energy efficiency in FDF is only 32% and PAF efficiency is 49.01%. Inefficiency of the air fan system is an impacted there are waste of electric energy amount of 13,352,929 KWh (13,35 GWh) a year with a financial loss of IDR 13,352,929,140. To overcome this condition, variable frequency drive (VFD) is installed which adjusted air flow as needed so that energy waste can be reduced. MATLAB simulation is proposed to analyze the VFD method. The result shows that by using VFD, 8,233,573.444 KWh (8.45 GWh) can be saved a year. Total cost benefits are IDR 8,233,573,444 as 32.1% of saving cost. Efficiency of FDF is 72.57 % and PAF is 66.84%.

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1. INTRODUCTION

The report of energy audits and performance tests in Power Plant Tanjung Jati B Jepara year 2018 shows that the air fan of boiler system is unefficient and over air supply, energy efficiency in the forced draft fan (FDF) () is only 32% and the primary air fan (PAF) efficiency is 49.01%. The flow rate capability of FDF is 1440 tons/day but the flow rate used is 512 tons/day and the flow rate of PAF is 450 tons/day but 197.4 tons/day is used in operation [1].

As a result, in this condition, there are waste of electrical energy in the electric motor operation. Moreover, it also resulted in financial losses [1]. According to the calculation data from the audit team, with the assumption that variable frequency drive (VFD) has been installed, the electric power loss in the FDF motor is 998.63 KWh or 6,391,246.93 KWh/year and in the PAF motor is 1,087.76 KWh or 6,961,684.21 KWh/year[1]. If calculated into rupiah (1 KWh = IDR 1000), the total financial loss is IDR 13,352,929,140 a year. The calculation is based on an FDF and PAF which integrated works together during 7286 hours[1]. To overcome unefficiency and over air supply, VFD is proposed. VFD regulates the air supply by adjusting the motor speed so that there is no excess air and its use is as needed, regulation of the motor by VFD also causes a decrease in the electrical power, therefore electric energy can be saved and efficiency of motors will be increased [2]-[15].

2. RESEARCH METHOD

The FDF and PAF VFD systems work in an integrated manner to supply air into the boiler, FDF provides air for the combustion process while PAF produces hot air to push coal into the combustion chamber. In existing system the air supply is higher than needs, so it is necessary to reduce the air supply by lowering the power using a VFD. In this way, the frequency, current and voltage in both of motors will also decrease and reduce the use of electrical power. FDF and PAF systems using VFD are shown in Figure 1 [6], [16]–[21]. The VFD block scheme is shown in Figure 2 [16], [20], [22]–[26].

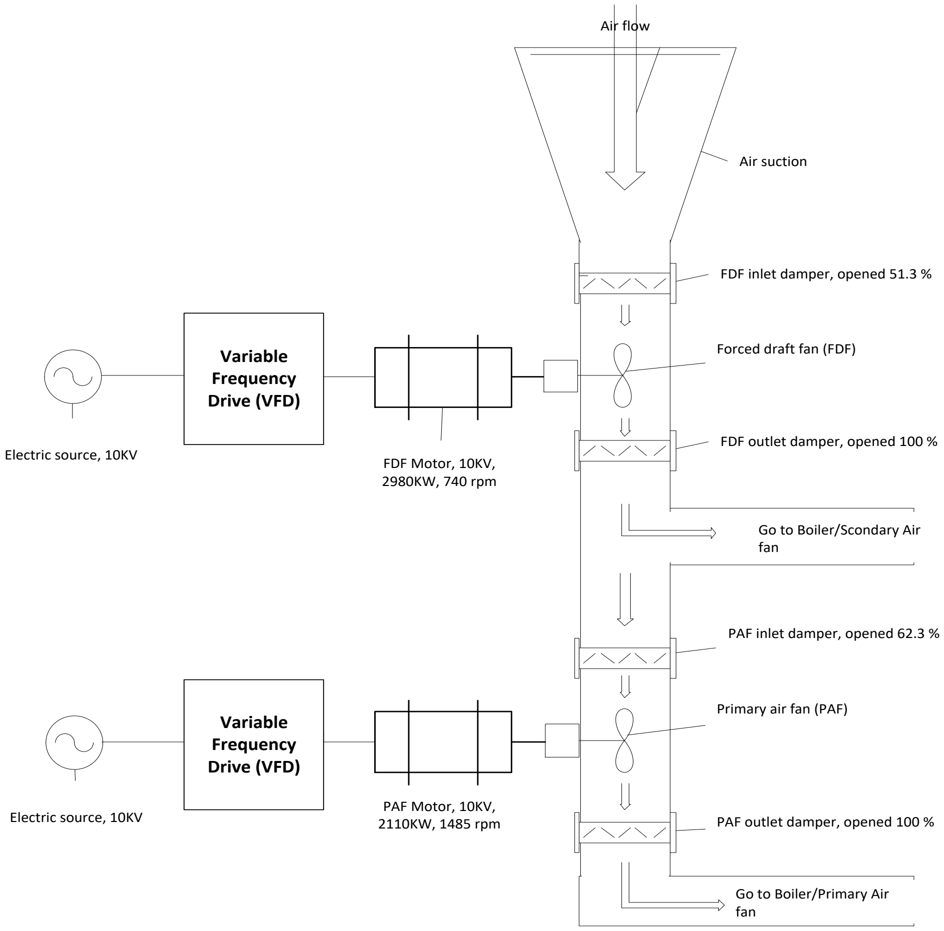

Figure 1. FDF and PAF System Model with VFD

Figure 2 shows the system model of the VFD circuit. The circuit consists of two parts of VFD FDF and PAF which are composed of block with respective functions. The blocks in the Figure 2 are entire VFD section which will be outlined in the MATLAB/Simulink circuit. VFD is simulated in MATLAB/Simulink shown in Figure 3 [6], [24], [26], [27]. Figure 3 is a simulation circuit of the VFD to drive the FDF and PAF motors. There are 2 VFD combined to drive 2 motors at once. In principle, the two parts of VFD have a similar work, the difference in parameters of motors. The supply voltage first passes through the rectifier unit where it is converted from AC to DC voltage. The DC voltage enters into filter to reduce the harmonic distortion during AC to DC conversion. Main part is an inverter which consists of six insulated gate bipolar transistor (IGBT) to convert DC to AC. Various frequency are carried out by using the pulse width modulation (PWM) method in the inverter device, this device gives a combination of sine and saw signal pulses that vary according to the required needs. Speed of the motor depend on adjusted frequency. Therefore, by adjusting the frequency through to the VFD we can control the speed of the induction motor in (1) [8], [13], [18], [28]–[30].

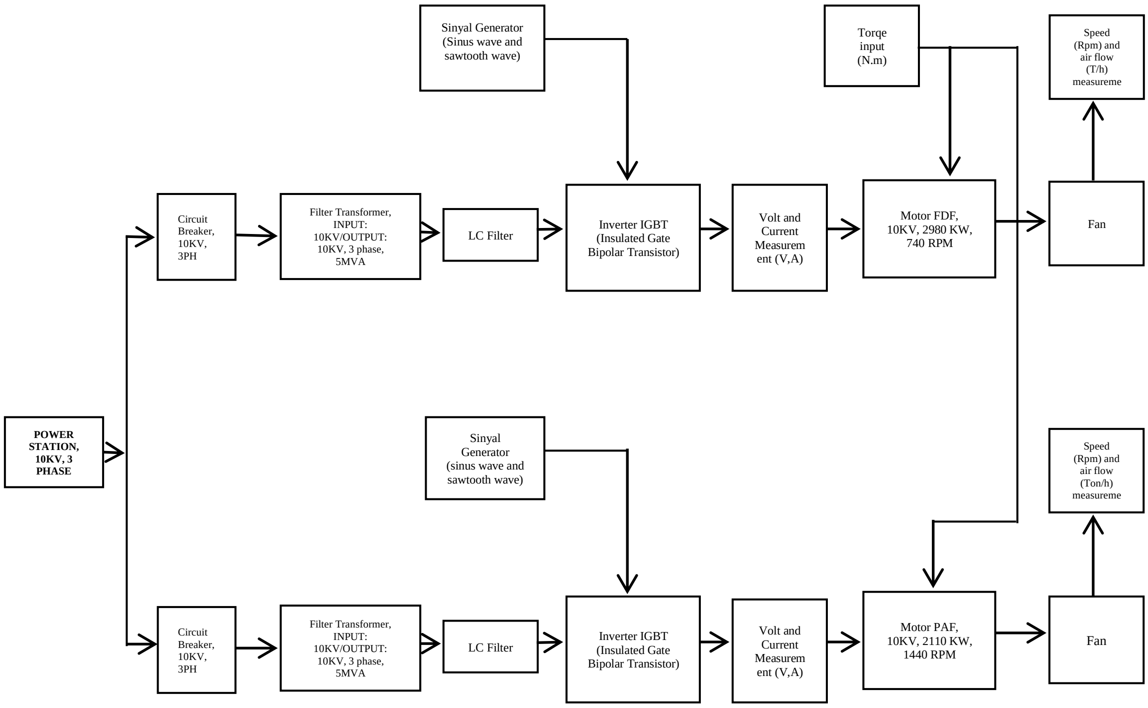

Figure 2. VFD block schematic

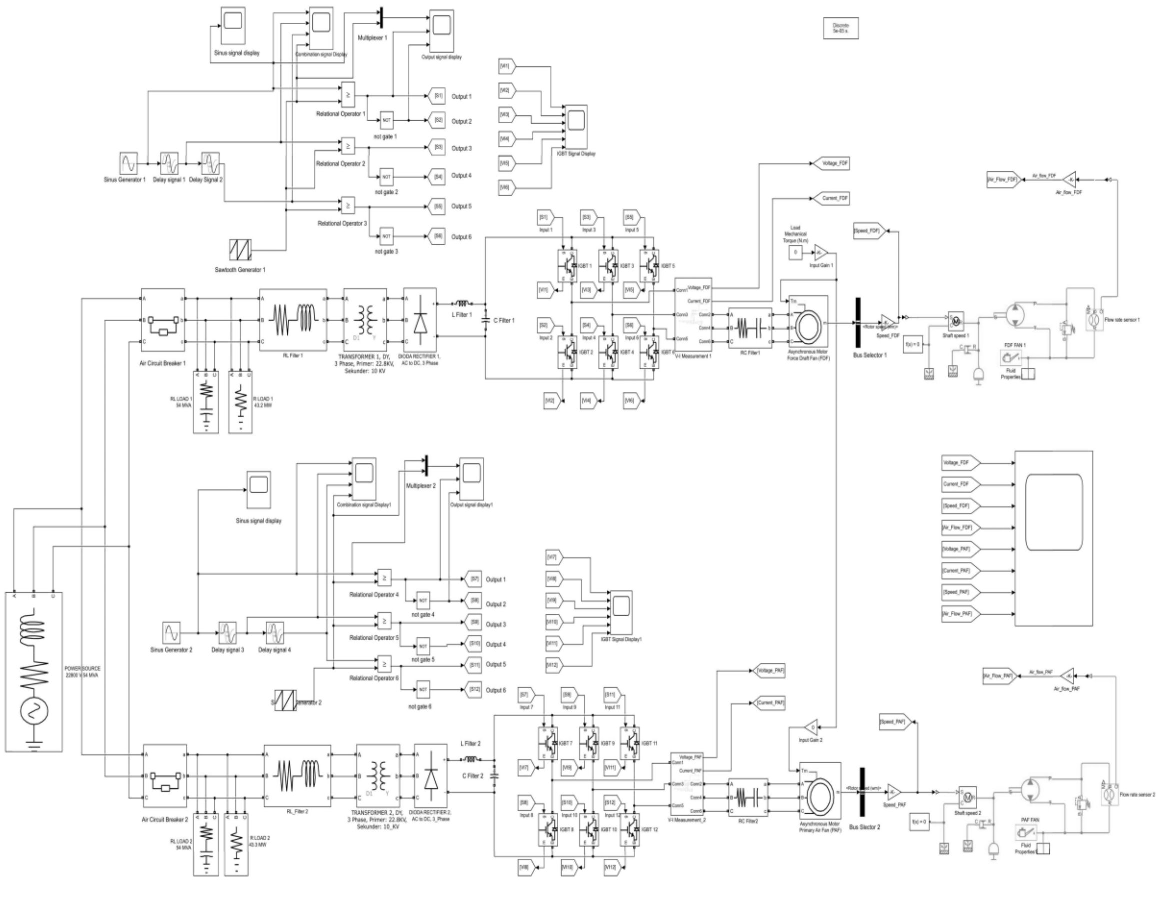

Figure 3. VFD simulation circuit

$$Speed\ (rpm) = (Frequency\ x\ 120)/pole \tag{1}$$

where:
Frequency: frequency in Hz
Pole: number of electric poles on the motor stator

Electrical power of VFD is calculated based on the load motors by taking voltage and current as shown in (2) [13], [30].

$$P = \sqrt{3}.V.I.Cos\ phi \tag{2}$$

where:
P: electrical power at load (W)
V: voltage at load (V)
I: electric current at load (A)
Cos phi: power factor at load

The financial cost calculation of electric power based on the amount of power during running hours as shown in (3) [1], [12].

$$Financial\ cost = P\ x\ Running\ hours\ x\ Price\ per\ KWH \tag{3}$$

where:
P: electrical power (W)
Running hours: VFD working duration in hours
Price per KWh: terms of electricity price per KWh

Saving opportunity is the difference between the installed device power and the device power in a simulation as shown in (4) [1], [12].

$$Saving\ opportunity = real\ power - simulated\ power \tag{4}$$

where:
Real power: total power of FDF and PAF for 1 year
Simulation power: total power of FDF and PAF in simulation for 1 year

Break even point is the period of investment return costs based on the value of savings obtained hours as shown in (5) [1], [12].

$$Break\ even\ point = Investment\ cost/finacial\ savings\ opportunity \tag{5}$$

where:
Investment cost: VFD installation fee
Financial saving opportunity: VFD savings value obtained in 1 year

Efficiency of FDF and PAF is comparison between total power output and total power input as shown in (6) [1], [12].

$$\eta = \frac{\mathrm{dP.Q}}{\sqrt{3}\mathrm{.V.I.COS\ phi}}\ x\ 100\ \% \tag{6}$$

where:
η: fan efficiency
dP: differential pressure
Q: air debit
V: voltage
I: current
Cos phi: power factor

The parameters entered into the VFD are shown in Table 1 [12], [13]

Table 1. VFD parameters

No.	Block name	Input parameter	No.	Block name	Input parameter
1	Power source	3 Phase Configuration: Yg Vrms: 22800 Frequency (Hz): 50	14	Relational operator 1,2,3,4,5,6	Relational: >= Output data type: Boolean
2	Air circuit breaker 1, 2	3 Phase Breaker resistance: 0.01 Ohm	15	Not gate 1,2,3,4,5,6	Operator: not Output data type: Boolean
3	RL load 1,2	Configuration: Y (grounded) Vrms: 22800 Frequency: 50 Active power: 54e6	16	IGBT 1,2,3,4,5,6,7,8,9,10,11,12	Internal resistance: 1e-3 Snubber resistance: 1e5
4	R load 1,2	Configuration: Y (grounded) Vrms: 22800 Frequency: 50 Active power: 43,2e6	17	V-I measurement 1,2	Measurement: phase to phase Current measurement: yes
5	RL filter 1,2	Branch type: RL Resistance: 0.1e-3 Inductance: 20e8	18	RC Filter 1,2	Resistance: 0,5 Ohm Capacitance: 0,1 F
6	Transformer 1,2	Connection: DY Nominal power: 6e6 Primary voltage: 22,8e6 Secondary voltage: 10e6	19	Asynchronous motor FDF	rotor type: squirrel cage Mechanical input: Torque Tm, 0 Nominal power: 2052220 W Voltage: 10000 V Frequency: 50 Hz Pole: 8 Slip: 0,0133
7	Dioda rectifier	Bridge arms: 3 Device: IGBT/Dioda	20	Asynchronous motor PAF	Rotor type: Squirrel cage Mechanical input: Torque Tm, 0 Nominal power: 1467630 W Voltage: 10000 V Frequency: 50 Hz Pole: 4 Slip: 0,0133
8	L filter 1,2	Inductance: 800 H	21	Bus selector 1,2	Mechanical motor speed (Wm)
9	C filter 1,2	Capacitance: 75000 F	22	Shaft speed 1,2	Velocity source, torque sensor
10	Sinus generator 1,2	Sine type: time based amplitude: 1 Frequency: 2*pi*50 (0 – 50 Hz) Phase: 120 rad Phase: 0	23	FDF fan	Displacement: 5e-06 m^3/rad Nominal shaft angular velocity: 750 Nominal fluid density: 14000000 No Load Torque: 10,9
11	Delay signal 1,3	Time delay: 0,0067 Initial buffer size: 1024	24	PAF fan	Displacement: 5e-06 m^3/rad Nominal shaft angular velocity: 1446 Nominal fluid density: 1400 No load torque: 0
12	Delay signal 2,4	Time delay: 0,013 Initial buffer size: 1024	25	Scope display	Sinus signal display Combination signal display Output signal display IGBT signal display Result signal display
13	Sawtooth generator 1,2	Frequency: 1e3 Phase: 120	26	Load mechanical torque	0 - 10,9 Nm

3. RESULTS AND DISCUSSION

3.1. VFD output signal

Simulation VFD using MATLAB/Simulink results of the signal form is obtained as shown in Figure 4. Figure 4 are output signal of VFD FDF and PAF, each signal showing voltage, current, motor speed and airflow. Simulation is done by vary the input frequency from 1 Hz to 50 Hz. The input frequency is carried out in the signal generator section. The sample frequency given to the simulation starts from 2 Hz to 50 Hz in increments of 2 Hz. Every increase in frequency in the generator signal will be followed by an increase in motor voltage, speed and air flow rate. The data from the simulation results are shown in Table 2.

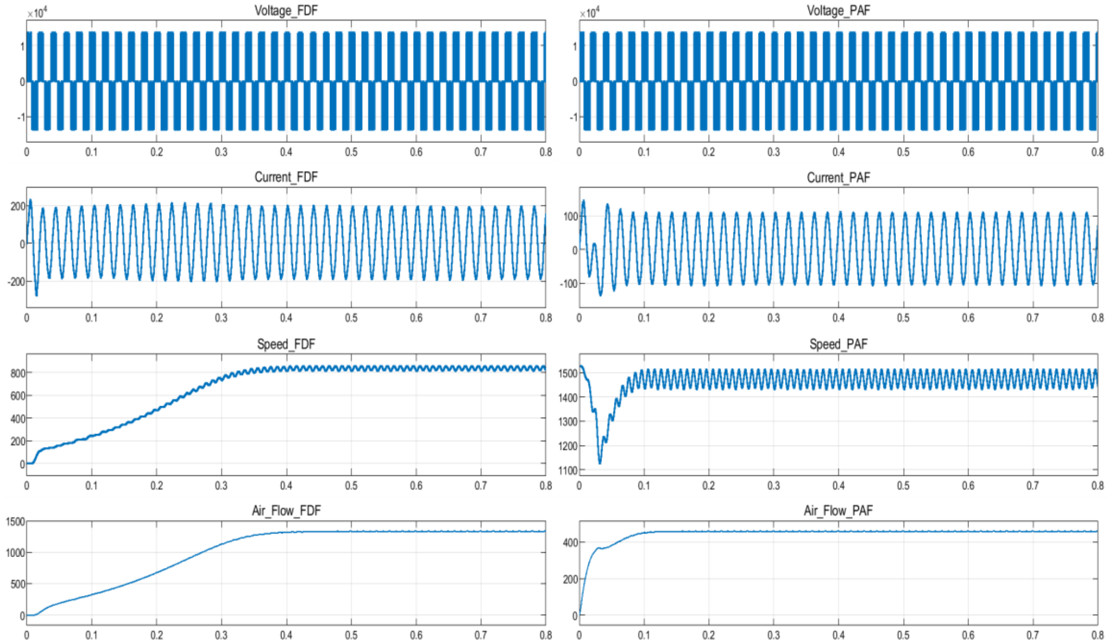

Figure 4. VFD output signal

Table 2 shows the lowest input frequency for VFD is 2 Hz and the highest is 50 Hz, the lowest FDF voltage is 2892 V and the highest is 9826 V, the current ranges from 29 A to 139 A, the lowest motor speed is 45 Rpm and the highest is 762 Rpm and air flow obtained the lowest 77 Tons/hour to the highest 1661 Tons/hour. PAF output obtained the lowest voltage is 2880V and the highest is 9816 V, the current ranges from 27 A to 98 A, the lowest motor speed is 295 Rpm and the highest is 1363 Rpm and the lowest air flow rate is 90 Ton/hour and the highest is 526 Ton/hour. Variation of frequency followed by voltage of the FDF and PAF motors is shown in Figure 5.

Table 2. VFD output value

No	Freq. input	FDF				PAF			
		Voltage (V)	Current (A)	Speed (Rpm)	Air Flow (Ton/hr)	Voltage (V)	Current (A)	Speed (Rpm)	Air Flow (Ton/hr)
1	2	2892	29	45	77	2880	27	295	90
2	4	3828	51	81	139	3924	41	294	81
3	6	4991	74	105	181	4993	54	328	94
4	8	5500	94	147	257	5497	67	378	111
5	10	5958	110	174	311	5959	77	430	130
6	12	6347	121	243	440	6334	86	485	149
7	14	6641	132	280	515	6629	94	537	169
8	16	6917	137	312	589	6906	98	583	189
9	18	7221	137	341	664	7207	98	626	210
10	20	7562	131	370	741	7561	93	668	232
11	22	7850	123	400	820	7842	87	713	255
12	24	8057	139	438	897	8048	78	762	279
13	26	8232	112	469	984	8216	69	814	303
14	28	8442	100	503	1060	8429	59	870	328
15	30	8586	93	534	1136	8570	51	927	352
16	32	8713	82	569	1215	8706	42	984	375
17	34	8858	70	601	1293	8842	36	1041	399
18	36	9004	59	637	1378	8991	32	1099	421
19	38	9137	58	671	1458	9124	31	1154	444
20	40	9174	63	704	1531	9165	34	1208	465
21	42	9394	73	734	1597	9381	40	1259	485
22	44	9476	84	760	1657	9471	47	1305	503
23	46	9515	95	781	1702	9500	54	1344	518
24	48	9587	107	790	1722	9586	62	1368	528
25	50	9826	118	762	1661	9816	70	1363	526

Figure 5 shows the variation of input frequency in VFD from 2 Hz to 50 Hz followed by a voltage change which increases from 2880 V to 10000 V. The variation of voltage followed the speed of the FDF and PAF motors is shown in Figure 6. It shows the various voltage followed by speed of the FDF and PAF motors. In the FDF motor, the lowest voltage is 2892 V followed by a motor speed of 45 Rpm, while the highest voltage is 9826 V followed by a motor speed of 762 Rpm. In the PAF motor, the lowest voltage is 2880 V followed by a motor speed of 295 Rpm and the highest voltage is 9816 V followed by a motor speed of 1363 Rpm. The various speed of the FDF motor followed by air flow is shown in Figure 7.

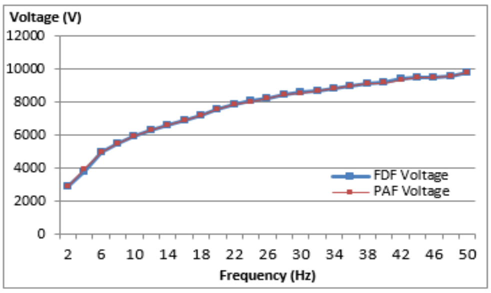

Figure 5. Correlation between various frequency and voltage

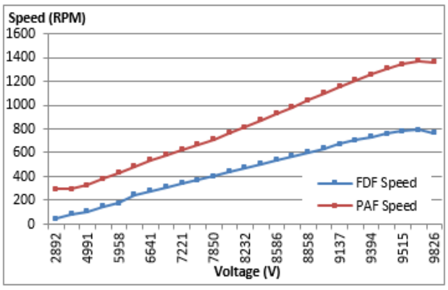

Figure 6. Correlation between various voltage and speed

Figure 7 shows the various speed of the FDF motor followed by air flow in the impeller fan which is the load on the motor. The lowest speed is 45 Rpm followed air flow rate at 77 Ton/hour and at the highest speed is 762 Rpm followed air flow at 1661 Ton/hour. The various speed of the PAF motor followed by air flow is shown in Figure 8. It shows the various speed of the PAF motor followed by air flow. The lowest speed is 298 Rpm followed air flow rate at 90 Ton/hour and the highest speed is 762 Rpm followed air flow at 1661 ton/hour.

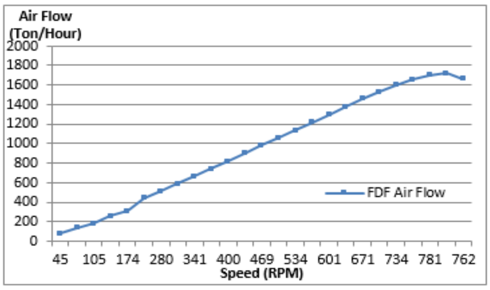

Figure 7. Correlation between various speed and air flow

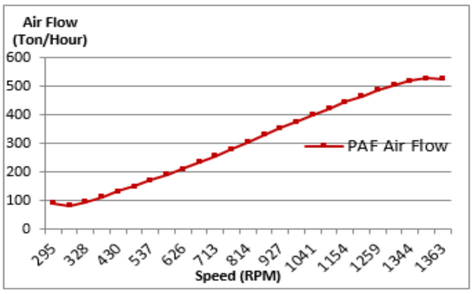

Figure 8. Correlation between various speed and air flow

3.2. Power calculation

The simulation power calculation is carried out based on the data from Table 2 VFD output value, from the data table searched flow rate value which is close to the actual flow rate value, the flow rate value is 984 Ton/hr for FDF and 232 Ton/hr for PAF. The flow rate will show the frequency, voltage, current and motor speed values, then the power will be calculated based on these values. Total running hours base on operation time a year is reduced by off time, the result is 7286 hours.

3.2.1. Total power of FDF motor

As shown (2) is used to calculate the value of the electric power in the FDF motor,

$$
\begin{aligned}
P &= \sqrt{3}.V.I.Cos\ phi \\
&= \sqrt{3}.8232.112.0.85 \\
&= 1{,}355{,}777{,}472\ W. \\
&= 1{,}355.78\ KW
\end{aligned}
$$

To calculate the electric power consumption for 1 hour then multiplied by an hour,

$$\begin{aligned} P &= 1{,}355.78\ KW.1\ hour \\ &= 1{,}355.78\ KWh \end{aligned}$$

The duration of the running hours in 1 year are 7286 hours, therefore the total power is calculated by multiplying the KWh by the duration of the year,

$$\begin{aligned} P &= 1{,}355.78\ KWh\ x\ 7286\ hours \\ &= 9{,}878{,}213.08\ KWh \end{aligned}$$

As shown (3) is used to calculate operating costs by multiplying the total KWh by the price per KWh, Total operating costs;

$$\begin{aligned} &= 9{,}878{,}213.08\ KWh\ x\ IDR\ 1000 \\ &= IDR\ 9{,}878{,}213.080 \end{aligned}$$

Efficiency of FDF calculated using (6),

$$\eta = \frac{\text{dP.Q}}{\text{P FDF}}\ x\ 100\ \%$$

Differential Pressure (dP) is pressure of flow rate FDF which opened damper 100%, 1 KPa. Flow rate value is 984 Ton/hr or 273.34 kg/s.

$$\eta = \frac{1 \text{ x } 273.34 \frac{\text{kg}}{\text{s}} \text{ x 60 second x 60 minute x 7286 hours}}{9{,}878{,}213{,}080 \text{ (Wh)}}\ x\ 100\ \%$$

$$\eta = 72.57\ \%$$

3.2.2. Total power of PAF motor

As shown (2) is used to calculate the value of the electric power in the PAF motor,

$$\begin{aligned} P &= \sqrt{3}.V.I.Cos\ phi \\ &= \sqrt{3}.\,7561.\,93.\,0.85 \\ &= 1{,}034{,}015{,}896\ W. \\ &= 1{,}034{,}016\ KW \end{aligned}$$

To calculate the electricity consumption for 1 hour, it is multiplied by an hour;

$$\begin{aligned} P &= 1{,}034{,}016\ KW.1\ hour \\ &= 1{,}034{,}016\ KWh \end{aligned}$$

The duration of running hours in 1 year is 7286 hours, therefore the total power is calculated by multiplying the KWh by the duration of the year. Then it is obtained,

$$\begin{aligned} P &= 1{,}034{,}016\ KWh\ x\ 7286\ hours \\ &= 7{,}533{,}840{,}576\ KWh \end{aligned}$$

As shown (3) is used to calculate operating costs by multiplying the total KWh by the price per KWh, Total operating costs,

$$\begin{aligned} &= 7{,}533{,}840{,}576\ KWh\ x\ IDR\ 1{,}000 \\ &= IDR\ 7{,}533{,}840{,}576 \end{aligned}$$

PAF efficiency calculated using (6),

$$\eta = \frac{\text{dP.Q}}{\text{P FDF}}\ x\ 100\ \%$$

Differential Pressure (dP) is pressure of flow rate FDF which opened damper 100%, 3 KPa. Flow rate value is 232 Ton/hr or 644 kg/s.

$$\eta = \frac{3 \text{ x } 64 \ \frac{\text{kg}}{\text{s}} \text{ x 60 second x 60 minute x 7286 hours}}{7{,}533{,}840{,}576 \text{ (Wh)}} \ x\ 100\ \%$$

η = 66.84 %

3.3. Savings opportunities

Savings opportunities is calculated using (4), existing motor power minus simulated motor power. The existing motor power is IDR 25,645,627.1 KWh/year and the simulation power (FDF+PAF) is 17,412,053,656 KWh/year.

$$\begin{aligned}&\textit{Saving opportunity}\\&= \textit{actual power} - \textit{simulation power}\\&= 25{,}645{,}627.1 - 17{,}412{,}053{,}656\\&= 8{,}233{,}573{,}444\ KWh/year\end{aligned}$$

$$\begin{aligned}&\textit{Financial savings opportunities}:\\&= 8{,}233{,}573{,}444\ KWh\ x\ IDR\ 1000\\&= IDR\ 8{,}233{,}573{,}444\end{aligned}$$

The opportunity for saving electrical power in a simulation is 8,233,573,444 KWh/year or in a percentage of 32.1%. Financially, the cost savings was IDR 8,233,573,444

3.3. Break even point

Based on the investment cost for the installation of VFD FDF of IDR 2,500,000,000 and a PAF VFD investment of IDR 2,000,000,000 [33], then the Break Even Point can be calculated using (5).

$$\begin{aligned}\textit{Break even point} &= \textit{investment cost}/\textit{savings cost per year},\\&= 4{,}500{,}000{,}000/8{,}233{,}573{,}444\\&= 0.546\ years\\&= 6.552\ months\end{aligned}$$

A summary of the overall data obtained is shown in Table 3.

Table 3. Summary of research data result

No	Parameter	Actual system		Simulation system		Saving opportunity	
		Motor FDF	Motor PAF	Motor FDF	Motor PAF	Motor FDF	Motor PAF
1	Running hours (hour)	7,286	7,286	7,286	7,286		
2	Flow rate (Ton/hour)	967.5	242.85	984	255		
3	Frequency (Hz)	50	50	26	22		
4	Voltage (Vrms)	9,955.62	9,955.62	8,232	7,561		
5	Current (Irms)	174.22	123.22	112	93		
6	Speed motor(Rpm)	740	1475	469	713		
7	Total power (KW) (P=√3.V.I.0,85)	2,052.22	1,467.63	1,355.78	1,034.016		
8	Total power each motor (KWh/year) (Px7286)	14,952,474.9	10,693,152.2	9,878,213.08	7,533,840.57	5,074,261.8	2,344,372.5
9	Total power for 2 motors (KWh/year) (PFDF+PPAF)	25,645,627.1		17,412,053.656		8,233,573.444	
10	Electric cost per KWh (IDR)	1,000		1,000		1,000	
11	Total operation cost (IDR/year) (Ptot x 1000)	25,645,627,100		17,412,053,656		8,233,573,444	
12	Approximate investation cost of VFD (FDF+PAF)						
13	Break even point (year) (Total investation/saving opportunity)						
14	Break even point (month)						

4. CONCLUSION

The consumption of electrical energy of FDF and PAF during 1 year without using a VFD is 25,645,627.1 KWh, while using a VFD is 17,412,053,656 KWh. So, the use of VFD is considered to be more efficient energy because of its lower electricity consumption. The opportunity for saving by using VFD is 8,233,573,444 KWh or 32.1% and the cost advantage obtained is IDR 8,233,573,444. Efficiency of FDF is increase to be 72.57 % and PAF is 66.84%.

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