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Single Phase to Three Phase Rotary Type Converter with Motor Control for AC Machinery Laboratory Equipment

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Abstract*: This research project was developed to introduce the phase conversion technology in augmenting the laboratory equipment in Don Honorio Ventura State University Electrical Engineering Department. The study was designed and developed by applying the standards in Philippine Electrical Code, National Electrical Code, Philippine Distribution Code and NEMA Standards. A Phase Failure Relay was specifically installed to ensure the single phase output is producing a three phase supply and a forward-reverse motor control circuit so that the evaluation of the phase converter will be more significant through several parameters. Voltage, current, and power were measured and recorded using six scenarios and four cases. Six scenario were performed to identify the suitable size of running capacitor. Four cases were also performed to evaluate the performance of the phase converter at different types of load condition. The measured voltage unbalance output of the phase converter at no load in this study is 1.83% that is accepted by the Philippine Distribution Code which has a standard limit of 2.5%; otherwise, the three phase is not consistent. The inductive loads perform better than capacitive loads when operating on a phase converter as the synchronous motor produces unbalance voltage in the system. It was also identified that phase converter consumes more power with 41.84% percent difference compared to normal three phase distribution when operating a ½ horse power (hp) induction motor load. This study served as an educational guide on how three phase load behaves in an innovated three phase supply not advisable for industrial or commercial use.

***Keywords* : phase monitoring, single phase, three phase, laboratory equipment**

I. INTRODUCTION

Three phase system is a type of poly phase system which is the most common method used by grids worldwide to transfer electrical power [1]. This system is generally more economical than single phase or two phase system because it uses fewer conductor materials to allocate electric power at similar voltage [2], [3]. In the case of motors, three phase motors have characteristics that make it unique: smaller size, lighter weight, cheaper cost [4], and has a better power factor [5] and it is well-known for its usefulness and economic benefit [6]. Three phase machines are commonly operated through a three phase power. However, one can actually use it in single phase supply with the aid of phase converters [7] – [12]. The technology of three phase distribution and machinery is essential when it comes to the field of Electrical Engineering (EE) [12]. AC Machinery is part of electrical engineering [5] that introduces three phase motors for generating both mechanical and electrical output [13]. It also expands the idea of EE students that motors are important when it comes to electrical engineering industry. However, the laboratory of the EE department in the university has only single phase supply. Proponents developed a single phase to three phase converter with voltage unbalance and single phasing detector for the laboratory purposes of AC Machinery and other concerning subject. Also, the proponents analyzed the performance of a three phase load in terms of voltage, speed, current, revolution per minute (RPM) and power when operating from a rotary phase converter [7].

Different types of converter were introduced in support with the improving technology like [14] – [18] that used rotary phase converter to drive a poly phase electric load. A phase converter was developed using transformers [19] – [21]. Phase converters are also constructed and designed through the use of induction motors like [22] – [25], and connected into a single phase supply to produce three phase supply [26] – [32]. While [33, 34] designed an apparatus and system that will produce a two phase power from a three phase supply using a delta configuration rotor and induction processed through phase converter. Several studies are also made on phase conversion system concerning electronics like [35] – [42]. However, in the present study a rotary phase converter was developed for instructional materials purposes. A rotary phase converter was constructed to produce a three phase supply from a single phase supply with an idler motor. Typically, idler motor is an induction motor due to its transformer connection (wye and delta) and will produce a third phase in the third winding [43] – [45]. The control circuit of the phase converter is a combination of contactor for motor starting application, overload relay, timer relay to control the startup of the idler motor, push buttons, and indicator lamp.

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The forward-reverse circuit is also a combination of contactor, overload relay, auxiliary contacts (electrical interlocking), push buttons, indicator lamp and phase monitoring relay to monitor the unbalance voltage and single phasing.

II. METHODOLOGY

The following algorithms were employed in developing a single phase to three phase converter:

A. Identification of Idler Motor

Rotary phase converters are commonly built with higher horse power (hp) rating as compared with that of the recipient's load. The horse power rating of the largest motor load to be connected determines the minimum converter rating needed [46]. There are ¼ hp and ½ hp three phase induction motors and ¼ hp three phase synchronous motor available in the EE laboratory of the university. These will serve as guides on what ratings to be used in constructing the converter. The horse power rating of the converter is generally two to four times the horse power rating of the load [47]. So, one hp phase converter was considered as the idler motor, which will serve as the third line of the three phase supply. Wires, capacitors and circuit protection ratings were considered to produce a better system. In the construction, wiring diagrams served as guide in the proper design of the project. For testing, the phase converter was evaluated with certain cases like no-load and on-load condition and also voltage and current were checked as well. Implementation of the project was done after all the testing.

B. Identification of System Components

Essential standards were utilized in determining the size of conductor wire, circuit breaker, grounding wire, capacitor and as well as in determining what type of circuit protection and enclosure box to be used.

Conductor Wire and Circuit Breaker

Every wire has a maximum electrical current it can transmit safely and has a correct breaker size to go along with it [48]. For the power circuit of the study, two sets of wires must be sized in a single motor phase converter installation: the three phase wires to the motor and the single phase wires to the supply. According to [49] section 4.30.14.2 and section 4.30.14.4, a half horsepower, 230 volts, single phase ac motors and three phase ac motors have a full-load current of 4.9 amps and 2.2 amps respectively. For the safety factor of the motors, the minimum ampere rating of circuit wire is 125% times the motor full load current [50], - [52]. Mathematically, the single phase wires to the supply will have a current of 6.125 amps and the three phase wires to the motor have a current of 2.75 amps. Therefore**,** for circuit breaker, 15 Ampere Trip (AT) for single phase ac motors [50] and 4 AT three phase ac motors were used [53] and the size of wires was 3.5 mm^2 equivalent to #12 American Wire Gauge (AWG) [50]. For the control circuit, the total current rating in the motor of the phase converter is 4.0 amps, then the size of wires was #18 AWG [54] and 3 AT for circuit breaker [53] considering forward and reverse control circuit cannot be run at the same time.

Grounding Conductor

For the safety of the operator it is important that a grounding conductor should be installed in all electrical equipment. For phase converter applications, the grounding conductors should be connected to the motor base, the phase converter enclosure and the grounding provision on the meter pole. The wire used in grounding application is based on [50], which is 3.5 square mm or #12 THW AWG. This will ensure a continuous ground return to carry any fault current back to the transformer and limit the voltage minimize electrical shock hazard.

Capacitor Size

An oil- filled type for running capacitor and starting capacitor was used [14], [55]. According to [56], [57], starting capacitor should be rated 450VAC, 300-400 microfarad, oil-filled type. This capacitor will function in the circuit when the idler motor starts to reach its required speed [47] and will be automatically disconnected when the idler motor achieves its full speed [58]. It is connected between the first terminal and the third terminal of the idler motor and wired through a magnetic switch to energize it.

Running capacitors, an oil filled capacitor, were used to correct the voltage unbalance in the phase converter and were determined using capacitor table [56] and tested at no load condition. For safety reason, running capacitors should not be expose to voltage above 10 percent of the nominal rating [59]. Then the voltage rating will be computed as 1.56 times the applied line voltage. Oil filled capacitors are used where high-peak voltages, high-current, and long operating life are needed [60]. This includes high-voltage filtering and energy storage, motor run, motor start, commutating, high-voltage lighting, heating, ventilation, air conditioning, and arc suppression applications. This type of capacitor is used to improve performance and efficiency to some degree. These are permanently connected into the first terminal to third terminal and second terminal to third terminal connections.

Circuit Protection The types of relays used in the study were power relays (magnetic contactor), overload relay and time relay. According to [61], [62] standard contactor for 1hp motor is NEMA 1 magnetic contactor with maximum horsepower capacity of 7.5hp at 3 phase, 230 V load voltage, 27 A continuous current rating. It will regulate changes in electrical frequency which comes from a power supply as well as the safety and convenience to connect and interrupt branch current is concern [63], [64]. The thermal overload relay will cut the power if the motor draws too much current for an extended period of time [65]. The time relay will control the circuit based on time particularly for motor starting [66], [67]. A 220 VAC, 5 amps contact rating is set for 0.3s. In motor starting application with starting capacitor, the contact should not exceed 0.5s otherwise it will damage the machine. The overload relay was computed using the formula for safety factors of motors: 1.25 x full load current of idler and motor load [68], [69]. In the study, overload relay was set to 4A as the full load ampere of the motor. A phase monitoring relay that is Phase Failure Relay (PFR) was installed with a buzzer to alarm if single phasing and voltage unbalance occur in the system.

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Based on [70] section 3.2.5.2, the maximum voltage unbalance at the connection point of any user shall not exceed 2.5% during normal operating conditions. And the NEMA definition of percentage voltage unbalance (V.U.) is

%V.U. = (Maximum Deviation of from average Voltage) / (Average of voltage) · 100 [71], [72].

Enclosure Box

A 20"x 16"x 8" NEMA 4X equivalent to IP66 type enclosure box as a standard of safety [73] was used. This type of enclosures is for either indoor or outdoor use to provide a level of protection to personnel against unintentional contact with the equipment and to provide a degree of protection against falling dirt, rain, windblown dust, splashing water, and corrosion [74].

C. Assembly of Power and Control Circuit

Power and control circuit of the idler motor is the main supplier of the three phase converter. Idler motor served as the third terminal lead of the three phase line as shown in Fig 1. The control circuit was designed through the combination of contactors, timer, indicator lights, push button rated, overload relay, and selector switch. While, the power circuit of the idler motor design is composed of contactors, starting and running capacitors.

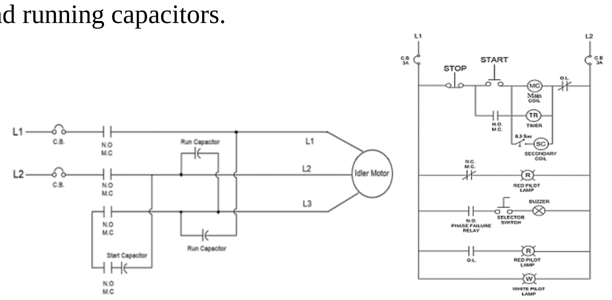

Fig 1. Power and Control Circuit of Idler Motor

Control and power circuit of the forward-reverse as shown in Fig 2. The forward and reverse motor control circuit serves as the load. The control circuit consists of contactors, auxiliary contacts, indicator lights, push buttons, overload and phase monitoring relay. Combination of Normally Open (NO) and Normally Closed (NC) auxiliary contacts were used for interlocking the motor control. While, power circuit consist of contactors and overload relay.

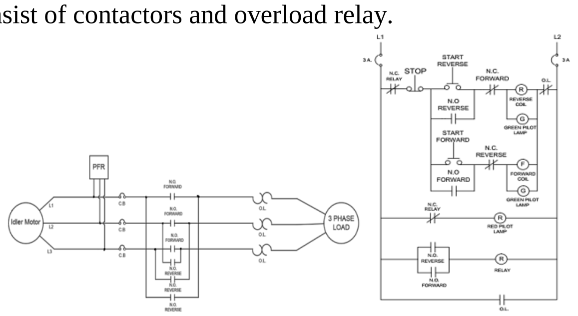

Fig 2. Power and Control Circuit of the Forward-Reverse

As seen in Fig 3 and 4, the control circuit was simulated in Logo Soft Comfort to check the precision of the design of the phase converter before the actual assembly.

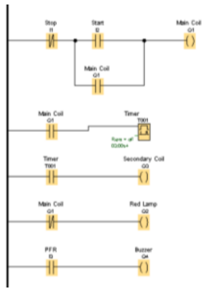

Fig 3. Control Circuit of the Idler Motor Simulation

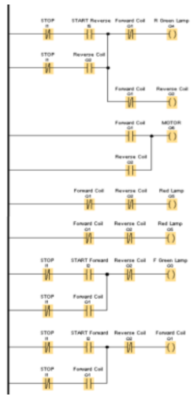

Fig 4. Control Circuit of the Forward- Reverse Simulation

D. Testing & Evaluation

The system was tested in different conditions in which the load can fulfill the rating of the phase converter. It was tested at no load condition with different capacitors rated at 440 V to identify the suitable rating for running capacitor. Voltage, and current were measured and evaluated in each scenario:

- Scenario 1: 15uF rated connected to L1-L3 (L_{13})
- Scenario 2: 15uF rated connected to L2-L3 (L_{23})
- Scenario 3: 15uF and 12uF connected to L1-L3 (L_{13})
- Scenario 4: 15uF and 12uF connected to L2-L3 (L_{23})
- Scenario 5: 15uF and 10uF connected to L1-L3 (L_{13})
- Scenario 6: 15uF and 10uF connected to L2-L3 (L_{23})

Selection of running capacitor was based on computed %V.U., a less than 2.50% is acceptable [70]. Scenario that produce the lowest %U.V. was tested at different load conditions:

- Case 1: At No Load Condition
- Case 2: At ¼hp Synchronous Load
- Case 3: At ¼hp Three Phase Induction Load
- Case 4: At ½hp Three Phase Induction Load

The phase converter was implemented in the laboratory of Electrical Engineering Department to demonstrate phase conversion in AC Machinery and other concerning subjects. Its performance was evaluated by comparing it on the normal three phase distribution

III. RESULTS AND DISCUSSIONS

This section provides data through the results of several testing and evaluation on the system that were done simultaneously to assess the performance of the phase converter using different load conditions.

Table I. Status of Phase Converter at Different Capacitors

Scenario	Current(A)			Speed (rms)	S.D.	Remarks
	L_1	L_2	L_3			
1	1.9	1.5	1.3	1798	0.3055	Tripped
2	1.9	1.3	2.3	1798	0.5033	Tripped
3	1.9	1.6	2.1	1798	0.2517	Tripped
4	1.9	1.6	2.1	1798	0.2517	Tripped
5	1.7	1.7	1.8	1798	0.0577	Normal
6	2.1	1.3	1.8	1798	0.4041	Tripped

Line to line voltages and currents were measured on a 230V single phase input supply. It is observed that every scenario, there was a constant speed in the motor at 1798 revolution per minute. After 3 s of operation, the PFR tripped on Scenario 1, 2, 3, 4, and 6. While, Scenario 5 has normal operation. It is shown in Table I; the normal operation standard deviation of the phase relay involves line current outputs of 5.77%.

Table II. Voltage Unbalance of the Phase Converter

Scenario	Voltage(V)			%V.U.
	L_{12}	L_{23}	L_{31}	
1	230	216	202	6.48
2	230	212	233	5.78
3	231	233	242	2.83
4	233	243	231	3.11
5	234	235	241	1.83
6	232	222	241	4.17

From the results as shown in Table II, capacitor value greatly affected the output line voltages of the phase converter and as the running capacitor tries to correct the voltage unbalance. Scenario 5 balances the output voltage of the phase converter and operates at normal condition with 1.83% voltage unbalance which is accepted in compliance with the [70] recommendation.

Based on Table III, the synchronous motor shows an abnormal status in the system (Case 2) due to the overcurrent detected by the overload relay that was set 4A and the PFR tripped indicated that the voltage unbalance in the system exceeded 2.5%. For induction motors, the system shows normal status in terms of current and line to line voltages. This verified that most of the phase converter only will be used with inductive loads [75]. The capacitors produce leading power factor in the converter [76], to neutralize the system an inductive load that produces lagging power factor [77] is an option.

Table III. Load Condition with Phase Converter

Case	Rotation	Voltage (V)			Current (A)			% V.U.
		L_{12}	L_{23}	L_{31}	L_1	L_2	L_3	
1	Forward	234	235	241	1.7	1.7	1.8	1.83
	Reverse	241	235	234	1.7	1.7	1.8	
2	Forward	232	206	221	5.4	5.3	1.6	7.37
	Reverse	222	237	205	5.4	5.3	1.6	
3	Forward	225	232	223	0.8	0.8	0.8	2.39
	Reverse	223	232	225	0.8	0.8	0.8	
4	Forward	233	232	231	0.3	0.3	0.3	0.43
	Reverse	231	232	233	0.3	0.3	0.3	

Based on the results on Table III and IV, a phase converter and normal operation (three phase distribution system) was compared in performance based on voltage and current outputs and real power. Percentage voltage unbalance of 2.3% of the three phase distribution are stable while acceptable unstable voltage unbalance was obtained in the phase converter.

Table IV. Load Condition at Normal Operation

At Forward Rotation		Voltage (V)			Current (A)		
Motor Load	**Rating**	L_{12}	L_{23}	L_{31}	L_1	L_2	L_3
Synchronous	¼ hp	220	218	215	2.4	2.3	2.5
Induction	½ hp	219	217	214	0.3	0.3	0.3
Induction	¼ hp	223	219	223	0.8	0.8	0.8

Table V. Input and Output Real Power in Watts

	Voltage(V)			Current(A)			Power
1 ϕ Supply (input)	232			1.06			110
3 ϕ Converter (Output)	L_{12}	L_{23}	L_{31}	L_1	L_2	L_3	687
	234	235	241	1.9	2.6	2.1	

Table V shows that an idler motor of 1hp phase converter at no load can only deliver 687 W much higher compared with the single phase operation. It is proven in Fig 5 that power consumed by the phase converter with ½ hp three phase inductor motor is higher than normal distribution for loaded system which also showed that there was an increase of 13.08 Whr at percentage difference of 41.84% power consumption based on laboratory class hours. This high energy consumption is due to parasitic power consumption according to [78].

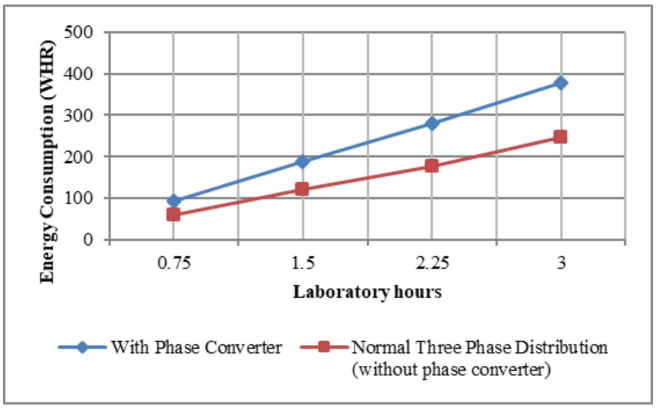

Fig 5. Consumed Power of the ½hp Three Phase Motor

IV. CONCLUSION AND RECOMMENDATION

The phase converter with phase failure was developed. This equipment can be a substitute to a three phase supply if the latter is not present or provided by the community electric cooperatives. It is for educational purposes only and not for commercial used since the power consumption is higher at a percent difference of 41.84% due to the phase converter itself. The experimental results also show that the phase failure relay cuts the power supply at 3 s after detecting voltage unbalance to protect both the phase converter and the load from overcurrent specifically when a synchronous motor was connected in the system.

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