Subject: Design Report for Phase Shifting Transformer Tap Changer

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Executive Summary

Our team has been requested to design for Schweitzer Engineering Laboratories a phase-shifting transformer and tap changer for use for testing in the University of Idaho power laboratory. This is the continuation of a project undertaken by Team Transformers. Prior to our team receiving the project, Team Transformers had already designed the 10 kVA transformer system to be used in this project, selecting and using transformers purchased by SEL. Team Transformers had also designed and assembled a tap changer in a radial configuration, which was designed to be manually adjusted through a handle connected to a special gear.

After considering various configurations, our team has decided to explore the use of a linear tap-changing system. Under a linear system, the contact points leading directly to the series transformer will be arrayed on a flat board. A carriage fitted with contacts leading to the shunt transformer will travel over the flat surface, stopping at specific intervals to correspond with each tap change. The system will employ a “make-before-break” approach: the traveling brushes will connect with the next row of contacts prior to breaking their connections with the last row of contacts. Because of the risks inherent in this process, speed and accuracy will be essential, as will a bridge resistor mechanism to minimize arcing.

Our team has made a preliminary investigation of track systems and made a concept drawing of a carriage and resistor bridge. We also performed a test of a carbon brush moving over contacts embedded in an acrylic board. Over the next semester we intend to further develop the linear system, which involves selecting the appropriate track system, designing a carriage and resistor bridge that can meet the target requirements, and integrating the foregoing elements with the appropriate propulsion and control mechanisms for actual laboratory testing.
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1.0 Introduction

Power flow transported over an alternating-current transmission line is represented by the equation

\[ P = \frac{V_r + V_s}{X_L} \sin \delta \]

where \( V_r \) and \( V_s \) are the sending and receiving voltages, respectively, \( X_L \) is the line reactance, and \( \delta \) is the angle (phase angle) between the two voltages. This equation illustrates that the flow of power through a line is inversely proportional to the line reactance and directly proportional to the voltages on the sending and receiving ends of the line multiplied by the sine of the electrical (phase) angle between the two voltages.

One way to vary power flow across a transmission line is to adjust the phase angle (\( \delta \)) of the voltage in the transformer to a larger or smaller value, which yields the equation

\[ P = \frac{V_r + V_s}{X_L + X_{PST}} \sin(\delta + \alpha) \]

where \( X_{PST} \) is the reactance of a phase-shifting transformer and \( \alpha \) represents the shift in phase. In a commercial setting, power transmission efficiency can be increased when a utility company can reduce power in one line where it is in abundance and shunt that additional power through an undertaxed transmission line while operating under load. In such a case, the difference in phase angles between the
input line voltage and the output line voltage is the angle of shift. One way to accomplish a change of phase angles is to use two transformers. One serves as a shunt unit and the other as a series unit. Because the arrangement in Figure 2 uses two transformers, this is known as an *indirect phase shifting* transformer. The shunt unit, called an *exciter*, regulates amplitude while the series transformer, called a *booster*, serves to inject voltage in the proper phase.
The phase-shifting transformer tap changer that we have been asked to build is intended for use in testing in the University of Idaho’s Power Laboratory. It is a small-scale device that will be operated in the immediate presence of the person or persons conducting the test. It must be able to meet the target specifications of performing a specified phase shift under load, and operate over a five-year period of testing. Our task is to focus on the physical integrity of the device; namely, designing a phase-shifting tap changer that can meet the target specifications and endure the rigors of operation in an academic testing environment.

2.0 Problem Definition

The team’s objective is to produce a phase shifting transformer tap changer that meets the specifications set forth herein. Specifically, PSTTC is tasked to come up with a physical unit that can complete tap changes of +/- 10 degree phase between the transformers used in the previous project, and operated in a laboratory testing environment, and operate under a current load of 15 amps. The device would be used in the University of Idaho’s power laboratory in the basement of the Buchanan Engineering Building. Our team was provided with the prototype built by Team Transformers at the start of the project, as well as the specifications that the existing prototype was designed to meet. PSTTC reevaluated these specifications after conferring with engineers from SEL and faculty on campus.

3.0 Specifications

<table>
<thead>
<tr>
<th>3.0 Specific Requirements</th>
<th>Description</th>
<th>Target Value</th>
<th>Acceptable Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Make Before Break</td>
<td>Must not cause arcing</td>
<td>Always connected to at least one contact</td>
<td></td>
</tr>
<tr>
<td>Solid Contact</td>
<td>Not just above, not barely touching. Makes good electrical connection</td>
<td></td>
<td>+/-.0.1 ohm</td>
</tr>
<tr>
<td>Contact force</td>
<td>Interfacial pressure required to make contact secure</td>
<td>8 lbf</td>
<td>5%</td>
</tr>
<tr>
<td>Contact area</td>
<td>Area of contact through which the current passes</td>
<td>0.196 in²</td>
<td>+/-0.0196 in²</td>
</tr>
<tr>
<td>Required current</td>
<td>Maximum current allowed to pass through contact</td>
<td>15A</td>
<td>+/- .5 A</td>
</tr>
<tr>
<td>720 Degrees of Rotation</td>
<td>The tap changer should stop at the maximum phase shift both positive and negative and not be allowed to continue in that same direction</td>
<td>720 degrees</td>
<td>+/- 5 degrees of rotation will be between taps if so, but not bridging max. and min.</td>
</tr>
<tr>
<td>-------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------</td>
<td>------------</td>
<td>------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Break after solid connection established on next tap</td>
<td>Smooth electrical response</td>
<td>Next tap contact has achieved greater than or equal to 75% of the contact area above</td>
<td>5%</td>
</tr>
<tr>
<td>Delay between phases</td>
<td>Response time to arrive at new phase</td>
<td>0.5 seconds</td>
<td>+/- 0.1 s</td>
</tr>
<tr>
<td>Speed of change</td>
<td>How quickly the tap changer should move between contacts</td>
<td>50-80 milliseconds</td>
<td>+/- 5 ms</td>
</tr>
<tr>
<td>Force</td>
<td>Manual force required to move the selector to the next position</td>
<td>5 lbf</td>
<td>+/- 0.1 lbf</td>
</tr>
<tr>
<td>Location</td>
<td>On transformer cart, top platform</td>
<td>No wires stretched above the ground so as to cause a tripping hazard. Line resistance less than 1 ohm</td>
<td>True</td>
</tr>
<tr>
<td>Security</td>
<td>Stability on the physical mounting</td>
<td>Handles input force up to three times that specified above with 0.118 in displacement from the equilibrium position</td>
<td>Force: 5% Displacement: 0.04 in</td>
</tr>
<tr>
<td>Ready access to all appropriate measurement points</td>
<td>Points of measurement must be accessible without digging through wires or detaching components</td>
<td>Connection type: per power lab standards, all inputs, outputs and taps must have an outside connection that can be made without moving, opening or detaching any of the components</td>
<td>True</td>
</tr>
<tr>
<td>Number of switching positions per phase</td>
<td>One switch position is required for each degree of phase change</td>
<td>Eleven switching positions</td>
<td>True</td>
</tr>
</tbody>
</table>

**4.0 Projected Deliverables**

We have been requested to produce a working device that will perform according to specifications set forth herein and be able to use the device in the University of Idaho’s power laboratory before the end of the project. Prior to this we are requested to produce a complete design package consisting of all drawings and details necessary to produce the device, as well as a 3-D model of our design fabricated on a 3-D printer.
5.0 Concept Development

We considered several options in choosing a design. The small scale of the system allows convective cooling from the ambient air which freed us from the limitations of having to incorporate a more complex cooling system. We wanted a design that was simple, durable, allowed maximum access and visibility and minimum wire tangling. Initially, we considered salvaging the prototype built by Team Transformers, or adapting the prototype’s manual input features to another type of tapping mechanism. We also considered a radial system that utilizes blade-shaped contacts. However, we decided to go with a linear system for its simplicity and the availability of off-the-shelf components to help us complete a substantial portion of the device. We first considered having one contact surface in the shape of a round roller moving over the second contact surface, which would be a flat surface. One design goal was to maximize design simplicity by eliminating the need for springs to provide contact force. However, problems of accuracy and tangling of wires persuaded us to discard this “rolling pin” design in favor of a design where both the moving and stationary surfaces are flat. Moving to this type of linear system

Figs. 3-5. Three concepts considered for our new design (from L-R): record player, rolling pin, knife blade configurations.
engendered design issues in five key areas: track systems, contact surfaces, a make-before-break mechanism, a drive system, and a control system. There is an added, unresolved issue regarding a desired switch to change the polarity of the system. But since the polarity switch is not a required deliverable, we have left that detail on hold pending successful completion of our principal tasks.

5.1 Track Systems

With the type of linear system that we are presently developing the carriage will have to be manipulated over eleven rows of contacts. It will travel a distance of approximately 1.7 inches per phase change and must stop precisely over each of the eleven stopping points along the track, which means both speed and accuracy are essential to the device. In terms of a track system the team has focused on two viable candidates: a screw-based track versus a rack and pinion system. With a screw system the carriage travels down the track on a threaded bar; this is basically what is known as a lead screw system. A ball screw system utilizes the same principle with the added feature of small, round bearings that
movie inside the screw threads to provide slightly greater accuracy. An affordable linear rail system can yield an accuracy of 0.012 inch over one linear foot of travel distance. In addition, lead screws are self-locking, leaving minimal play in the system. The disadvantage is that screw-based systems are typically more expensive than rack and pinion systems and would be difficult to operate effectively in a manual input setting. Rack and pinion systems utilize a rotating gear that interacts with a track to drive the carriage down the track. A feasible rack and pinion system would essentially consist of a motor and motor mount, a drive gear, and a driven gear to pull the carriage down the track. It would also require an external braking system to ensure that the carriage stops where it’s supposed to. With either lead screw or rack and pinion, total needed track length under present design is approximately 15 inches.

5.2 Contact Surfaces

Contacts on the carriage comprising the bridge resistor will be carbon-graphite. The graphite brushes were selected based on their known durability, low cost, and the electrical transmissivity requirements of the system. In addition, the variety of shapes and sizes for graphite brushes improves the team’s options in terms of designing the overall make-before-break system. Under the planned linear system, contacts leading to the series transformer will be copper with a dimension of 0.5 inch.
diameter each and approximately 0.75 inch long. There will be a total number of 33 contacts, corresponding to three contacts per tap: ten taps per phase on the shunt transformer, and one tap for zero phase shift. The spacing of these contacts will be dependent upon the span of the resistor bridge, which, in turn, will determine the necessary speed of the motor to drive the resistor bridge. A wave spring is positioned beneath each contact in order to provide the requisite contact force.

5.3 Make-Before-Break System (Resistor Bridge)

One of the challenges of changing phase under load is to avoid arcing, which can damage equipment. The other problem is prevention of backcurrent in the transformer. To solve these problems PSTTC proposes using a make before break contact in the form of a resistor bridge. The alternative is to use a reactive bridge (or inductor bridge) which is more complicated to fabricate and design. The resistor bridge will consist of three carbon brushes side by side, separated by a thin, insulating material. The outside brushes, each attached to a resistor, will form the resistor bridge, while the inside brush will comprise the main contact surface. In order to change settings our selector contacts with the resistor bridge connection will slide across a line of tap connections, bridging two before moving onto the next setting. The proposed brush dimensions are length of 1.75 inches, a width of 0.5 inches and a thickness of 0.375 inches, giving a contact surface area of 0.1875 inches (for a rectangular surface). This surface

Figs 7 and 8. Two views of carriage holding three carbon contacts comprising the resistor bridge.
area, together with a rated electrical transmissivity of $80\frac{A}{\text{in}^2}$, will allow the device to meet the 15A requirement. The dimensions of the make-before-break system will be approximately 1.225 inches wide, which will dictate the spacing of the contacts leading to the exciter transformer. The time in which a bridge is maintained between the last row contacts and the next row is .05 seconds. In deciding the type of resistors for this bridge we need to consider our optimum resistor values. High-ohm resistors dissipate less power but cause a greater current interruption. Low-ohm resistors, on the other hand, experience less current interruption but have a greater potential for overheating.

5.4 Drive and Control Systems

The proposed linear track system will require a means to propel the carriage up and down the track. One option is to move the tap changer by hand by way of a lever or handle. Manual input was incorporated into the Team Transformers prototype, and our team considered ways in which we could retain that aspect in our design as well. However, we have increasingly come to favor a motorized system for greater accuracy in the tap-changing process, improved safety to the system operator, and the aforementioned constraints imposed by the screw-based linear rail systems.

The drive system, or stepper motor, that we select will determine the ease of use, speed, and to some extent the accuracy of the whole system. The favored model is the L/R stepper motor drive with a

Fig. 9. Carriage traveling over copper contact surface (acrylic board not included in view).
half step mode. The half step mode refers to the number of steps that the drive takes for each interval. A full step is 360 degrees divided by the number of rotor teeth on the motor (a standard stepper motor will have approximately 200 rotor teeth). A favorable feature of the half step mode is that it determines how many steps you take at a time and therefore allows you to divide the positioning into smaller increments, leading to greater accuracy. The speed of the motor we select will be determined by the diameter of the excitation contact surfaces and the span of the resistor bridge. The diameter of the copper contacts is 0.500 inches and the span of the proposed resistor bridge is 1.225 inches, giving a total center-to-center distance of 1.725 inches, or slightly less than this if make-before-break is to be maintained. Removing 0.005 inches from the center-to-center distance and dividing by the proposed speed of 0.50 seconds to change taps (allowing .05 seconds to maintain the bridge between rows of taps) gives a motor speed requirement of .863 feet per second.

The other constraints on the type of driver system we select are the electronics and software or programming that the driving device will be using, comprising the control system. Some of the systems we are looking at, such as the Haydon-Kerk linear track systems, come the option of a control system on some models.

5.5 Polarity Switch

To move from positive to negative phases requires either rewiring the device or implementing a polarity switch. It is the client’s wish that this be done using the latter method. This is a lingering problem that the previous design team attempted to solve with a grooved hub coupled to a Geneva gear; however, the switch was not completed. Switching from a radial to a linear system created the necessity of having to rethink both implementing the polarity switch with this device and, if so, the best way to do so. As mentioned previously this is not a required deliverable on the project and accordingly has not been given detailed design consideration.
6.0 System Design

Each transformer consists of ten winding locations to which the tap changer will be connected. This connection occurs through copper contacts set into the bottom base plate which is made of non-conducting acrylic. In total there will be three rows of eleven contact positions: ten tap locations as well as a neutral position. To provide the required contact force between selector heads and copper contacts, wave springs will be inserted below the copper contacts in the base plate for optimum resistance. Across each row of copper contacts will glide one of three selector heads. The selector heads consist of three carbon brushes connected by a resistor bridge. These selector heads will sit inside a carriage connected to the ball screw linear motion system which will move the carriage between tap locations. Linear motion will be provided through either a human-driven crank system or a stepper motor. The system is to be supported on the top shelf of a cart, while the transformers are contained on the bottom shelf. This provides the necessary ease of movement and optimum storage.

7.0 Future Work

| January                      | • Finalize all preliminary testing  
|                             | • Select materials  
|                             | • Complete detailed drawing package of design  
|                             | • Design review  
|                             | • Begin machining in shop  
| February                    | • Complete machining  
| March                       | • Testing and redesign  
| April                       | • Final product by Expo  
|                             | • Final reports and documentation  |
8.0 Budget Summary

<table>
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<tr>
<th>Item</th>
<th>Cost</th>
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<tr>
<td>Electrical Components</td>
<td>$300</td>
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<tr>
<td>Carriage, Guide Rails, Body</td>
<td>$150</td>
</tr>
<tr>
<td>Actuation Systems: Rack and Pinion</td>
<td>$100</td>
</tr>
<tr>
<td>Actuation Systems: Prefabricated Track</td>
<td>$500</td>
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<tr>
<td>Control System</td>
<td>$400</td>
</tr>
<tr>
<td>Polarity Changing Unit</td>
<td>$ (unknown)</td>
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<tr>
<td><strong>Total Projected Budget</strong></td>
<td><strong>$2000</strong></td>
</tr>
</tbody>
</table>

9.0 Recommendations

For the final design the make-before-break design is recommended because it is simple and straightforward in its construction. These characteristics are to be implemented in the linear motion system as well. For this reason the linear track system is recommended. It requires lower tolerances than other designs and will therefore be easier to manufacture and assemble. The make-before-break design issue will be solved using a contact head that consists of a resistor bridge across three carbon brush contacts. This will limit the amount arcing and reduce the back-current during make-before-break. A ball screw system is recommended for the linear motion system as it will provide the desired accuracy and speed. The linear motion can be driven by human input; however, a stepper motor is recommended as it would provide a high degree of simplicity in achieving the desired tap change specifications.

10.0 References

