INTRODUCTION

In this series of articles, we will be looking at each of the main stages of the electrical power system in turn. As you will recall from our Introduction to Electrical Power Systems, this can be broken down into five key areas:

- Generation
- Transformation
- Transmission
- Distribution
- Protection

Each article in this series will comprise a brief overview of the topic in question, and will focus on the learning objectives within that field. We will relate these to our individual Power System Laboratory modules, and detail the range and depth of the experimental scope, highlighting important concepts along the way.

Finally, we will discuss our Power System Trainer, and detail the added experimental scope that an integrated system will cover, and how this relates to some of the key issues in the power industry.

THE GENERATION OF ELECTRICAL POWER

As discussed in the Introduction to Electrical Power Systems, typical thermal or nuclear power stations, which produce approximately 80% of the world’s electricity, generate tens of thousands of amps at tens of thousands of volts. In order for this to be cost effectively supplied to consumers via the grid, it must be transformed to suitable levels of voltage that minimise the losses caused by high currents being transmitted along a conductor with a given resistance. This is achieved by raising the voltage to several hundreds of thousands of volts (“boosting”), thereby reducing the current proportionally. As power losses are proportional to the square of the current, energy losses at high voltages are massively reduced.

At the other end of the transmission grid, these high voltages are progressively stepped down within the Distribution network until it is delivered to consumers at levels in the hundreds of volts.
This stepping up and stepping down of the voltage is achieved by using large power transformers in the system. These utilise the principle of electromagnetic induction which transfers electrical energy from one circuit to another.

In its simplest form, a transformer consists of a primary winding coiled around part of a common core around which is also coiled a secondary winding. The ratio of the number of coils in each of these windings determines the ratio of the input and output voltages.

A SIMPLIFIED SCHEMATIC OF A BASIC TRANSFORMER
(Source: CC BY-SA 3.0 - BillC at the English language Wikipedia)

In the power industry, these transformers are much more sophisticated, being very large, heavy, expensive precision-built units, but the essential principle of operation is the same as in the simplified example above.

The PSL20 Transformer Trainer is a very flexible training module - it has been specifically designed to be, in effect, a comprehensive "toolkit" - that enables the student to study of a vast host of transformer configurations. A selection of these experiments are described in the manual, but they by no means represent the full array of possibilities. Among the experiments that are described in the manual, the following topics can be studied:

- Voltage and turns ratios
- Parallel and series windings, delta, star and interstar
- Phasing of windings
- On Load (Current) Ratio Checks
- Open and short circuit tests to find transformer properties, including losses and efficiency
- Balanced and unbalanced loads
Phase differences in popular three phase transformer connections
Three to two-phase connections (Scott and Le Blanc)

Further experiments, which are not specifically detailed in TecQuipment’s manuals, include:

- No load voltage ratio and polarity of a single phase transformer
- Direct load tests on a single phase transformer
- Back-to-back tests on two single phase transformers (Sumpner Test)
- Efficiency of a transformer from its losses
- Open & short circuit tests on a single phase transformer
- The auto-transformer
- Equivalent circuit of a three winding transformer
- Temperature rise tests on a transformer
- Separation of iron losses into hysteresis & eddy current components
- Effect of abnormal voltage & frequency on transformer characteristic
- Generation of Harmonics in Single phase transformer
- Harmonics and unbalanced loading in a three phase transformer bank
- Effect of core type construction on harmonics in a three phase transformer
- Three to two phase transformation - the Scott connection
- Three to two phase transformation - the Le Blanc connection
- Three Phase transformer connections
- Direct Load tests on three phase transformer
- Equivalent circuit & regulation of a three phase transformer
- Core and winding temperatures in a three phase transformer (thermal tests)
- Differential protection of a delta-star connected transformer, when used with the Differential Protection Relay (PSA15)

We shall take a brief look at the PSL20 itself, and how it fits into the overall context of our Power Systems range, before turning to these experiments in a bit more detail, and then we shall look at Transformation as part of the integrated Power System Trainer.
THE TECQUipment POWER SYSTEMS RANGE

TecQuipment manufactures a comprehensive range of trainers to cover all the aspects of an electrical power system, ranging from a suite of standalone Power Systems Laboratory trainers which look at each of the aspects of Power Systems in turn – Generation, Transformation, Transmission, Distribution and Protection, through to an all-encompassing Power Systems Trainer that combines all these elements in one unit, and allows for further investigations from an integrated systems standpoint.

In electrical power systems courses in universities and colleges, it is often easier for students to understand the principles involved with each of the elements of an electrical power system separately. Only then can students progress towards studies of more complex systems when several of these elements are interconnected and working together.
THE TRANSFORMER TRAINER (PSL20)

Investigates the principles and operating characteristics of single-phase and three-phase power and distribution transformers

Recommended Ancillaries for further experiments:

- Two Channel Oscilloscope (OS2)
- Differential Protection Relay (PSA15)
DESCRIPTION OF THE PSL20 AND KEY EXPERIMENTS

The PSL20 is a self-contained standalone module, and is comprised of several key elements;

- Upper panel containing analogue meters and protection relay
- A variable autotransformer
- Delta-star wound three phase transformer
- Single and three phase educational transformers
- Multifunction instruments and transducers, and Phase Shift meter
- Resistive, capacitive and inductive loads
- Current transformers

UPPER PANEL

Analogue Meters are provided, in addition to the multifunction instruments in the lower panel, to provide greater flexibility for different circuits, where the use of the multifunction instruments is not practical.

The Directional Overcurrent Relay which is incorporated in the upper panel familiarises students with the use and operation of protection relays in three phase circuits, and also acts as additional circuit protection during experiments. An optional Differential Protection Relay (PSA15) can also be used to extend the scope of experiments in protection techniques.

LOWER PANEL

The Variable Autotransformer allows the student to create a variable ac voltage source, which assists exploration of some fundamental principles of transformers, such as the magnetic field within the core and transformer ratio.

The TX2 delta-star wound three-phase transformer (Dy11) allows students to perform tests on a fixed-configuration three-phase transformer. In conjunction with the optional PSA15 relay, students can extend these tests to cover differential protection tests.

EDUCATIONAL TRANSFORMERS (TX3, TX4, TX5 AND TX6)

The PSL20 contains a unique set of single-phase and three-phase educational transformers. TX3 is a three-phase, shared core, double wound transformer, and incorporates thermocouples in the core and in the windings. TX4, TX5 and TX6 are single-phase, double wound transformers with tertiary windings, and one of them contains thermocouples, as with TX3. In the single-phase transformers, the primary and secondary windings are in two sections for easy series or parallel connections.
These transformers have been specially designed and manufactured for the PSL20 so that their per unit values of losses and reactances are similar to those of much larger transformers. This makes the experiments that the student does, and the results that are obtained from the experiments, both meaningful and scalable to real world systems. In addition, in order to simplify study of the experimental results, the transformers work at one volt-per-turn, so that the no-load output corresponds directly to the number of secondary turns.

The flexible design of the educational transformers means that they can be used in any of the most common three-phase connections:
## Phasor Diagrams for Three-Phase Transformers

<table>
<thead>
<tr>
<th>Vector Symbols</th>
<th>Line terminal markings and vector diagram of induced voltage</th>
<th>Winding Connections</th>
<th>Phase Displacement</th>
<th>Main Group Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yy0</td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td>0°</td>
<td>1</td>
</tr>
<tr>
<td>Dd0</td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dz0</td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zd0</td>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yy6</td>
<td><img src="image9" alt="Diagram" /></td>
<td><img src="image10" alt="Diagram" /></td>
<td>180°</td>
<td>2</td>
</tr>
<tr>
<td>Dd6</td>
<td><img src="image11" alt="Diagram" /></td>
<td><img src="image12" alt="Diagram" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dy1</td>
<td><img src="image13" alt="Diagram" /></td>
<td><img src="image14" alt="Diagram" /></td>
<td>-30°</td>
<td>3</td>
</tr>
<tr>
<td>Yd1</td>
<td><img src="image15" alt="Diagram" /></td>
<td><img src="image16" alt="Diagram" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DyII</td>
<td><img src="image17" alt="Diagram" /></td>
<td><img src="image18" alt="Diagram" /></td>
<td>+30°</td>
<td>4</td>
</tr>
<tr>
<td>YdII</td>
<td><img src="image19" alt="Diagram" /></td>
<td><img src="image20" alt="Diagram" /></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
As well as the three-phase connections above, students also have the capability to perform three to two-phase connections – specifically the Scott Connection and the Le Blanc Connection:
Gaining an understanding of these different configurations, their advantages and disadvantages, their characteristics and performance, enables the student to determine the suitability or otherwise of any particular configuration in any given real world electrical power system. By studying these different configurations, students gain an appreciation for the various parameters governing why a particular configuration is suitable in any given context, such as:

- Voltages and insulation – star v delta, high v low voltages
- Optimum configurations for step-up and step-down transformers
- Mechanical strength and cost-effective construction, particularly the relative amounts of copper required for equivalent configurations
- The presence and effect of Harmonic distortion
- Electromagnetic compatibility (EMC)
- Load balancing
- Phase displacement
- Neutral and earthing requirements for different types of loads
- Uses and ratings of Tertiary windings

A set of transducers in the lower panel allows the student to safely connect an oscilloscope, enabling voltage and current waveforms to be studied, as well as the phase relationship between them.
PROTECTION SYSTEMS

Built in to the PSL20 is a MiCOM Directional Overcurrent relay. This enables students to acquaint themselves with the operation and use of an industrial relay, as they would find in real power system applications. Topics able to be studied include:

- Directional/Non Directional Earth Fault
- Directional/Non Directional Phase Overcurrent
- Wattmetric Protection (Pe or Ie cos)
- Broken Conductor Detector
- Under Current
- Negative Phase Sequence Overcurrent
- Thermal Overload
- Under voltage
- Over voltage
- Residual Over voltage
- Blocking logic
- Cold Load Pick Up

To complement these studies in protection, an additional optional relay, the PSA15 Differential Protection Relay, is available.

FURTHER STUDIES IN TRANSFORMATION

The PSL20, as we have seen, is a comprehensive “tool kit” that enables the student to understand the fundamental operating principles of single and three phase transformers, and the relative merits of a wide range of connection configurations.

For further, more detailed study of Transformation within the context of an integrated Electrical Power System, the PSS1 Power Systems Trainer takes the student to the next level. Whilst there is some overlap, obviously, between the PSL20 and the PSS1 in terms of the experiments that can be performed, the PSS1 is focused much more on the role and interaction of transformation within the wider context of a real world system. Some of the experiments that the student performs with the PSL20, such as the more fundamental characteristics of a transformer for example, are not covered by the PSS1. Instead, it is assumed that the student has already covered these topics and developed a mastery of the fundamental principles of transformation with the PSL20.

The next section, therefore, looks at the capabilities of the PSS1 and the scope of experimentation that it offers in the context of transformation.
THE POWER SYSTEMS TRAINER (PSS1)

The PSS1 is a self-contained unit that replicates all parts of an electrical power system and its protection, from generation through to utilisation.

THE PSS1, SHOWING THE GRID, GENERATOR AND DISTRIBUTION TRANSFORMATION SECTIONS
THE SECOND GENERATOR (PSS3)

The PSS3 is a self-contained motor and generator set that connects to the Power System Trainer (PSS1) for extra experiments in central and embedded generation.

DESCRIPTION OF THE PSS1 AND PSS3, AND KEY EXPERIMENTS IN TRANSFORMATION

The PSL range is very much geared towards understanding the fundamental principles underlying each of the main elements of an electrical power system individually. In the real world, of course, we rarely consider any of the individual elements of a power system in isolation. The PSS1 Power Systems Trainer therefore looks at the entire system as a whole, and is focussed on how the different elements interact with each other in a holistic system.

The PSS1 is essentially a scaled down version of a real-world power system, and uses many of the features of the PSL range, such as the per-unit-value system, identical Motor and Generator as the Prime Mover and industrial Protection relays. The student therefore naturally progresses from the individual isolated module approach of the Power Systems Laboratory range, to a systems approach in a smooth and seamless transition.

The PSS3 is an optional add-on to the PSS1, comprising a duplicate Motor and Generator, for even further exploration of transformation within an integrated system.
The construction and layout of the PSS1 makes it an extremely versatile trainer, allowing the student virtually unlimited flexibility and experimental scope. As a result, the PSS1 is ideally suited for advanced project work and is a perfect system to perform scenario-based learning within either an academic environment, or in a more industrially-focused technical training environment.

The PSL20 focussed on the fundamental principles that govern the operation of transformers. With the PSS1 Power Systems Trainer, it is assumed that the student has mastered these fundamental principles, and the focus is very much on the integrated power system as a whole. Transformation is effectively treated as a means to an end as far as the wider system is concerned, the optimum transformer configuration effectively being treated as a given, in the context of a real-world system.

However, there are some Transformation topics which are explored in further detail with the PSS1.

**TRANSFORMERS IN PARALLEL**

In most distribution sub-stations, the step-down transformers are arranged in parallel. This serves a number of purposes - it allows for increased capacity; it enables redundancy to be built in to the system, thereby increasing its resilience; and it allows for an individual transformer to be shut down for maintenance, for example, without having to interrupt the output from the entire sub-station.

Having transformers in parallel can lead to particular problems in the system, and it is necessary to ensure that the two (or more) transformers are matched to enable efficient management of the electrical supply.

If we have transformers in parallel that have unequal tapping ratios, there will be a circulating current within the system. This has the effect of creating a small voltage generator within the transformer loop.

The PSS1 allows the student to set unequal taps on the two distribution transformers, enabling investigations into the current, power and reactive power within the system, thereby examining the variation between the primary currents of the two transformers.

Similarly, the student can investigate the effect of having unequal impedances in the transformers, and the effect that this has on the load sharing within the system. Applying resistive, capacitive and inductive loads on transmission lines of varying lengths allows the student to study in detail the effect that these loads have on the behaviour of a wide range of representative networks.

Having unbalanced loads in the network allows the student to perform experiments in symmetrical component analysis by investigating the current flow in the primary and secondary lines of a distribution transformer when the delta secondary supplies a single load connected...
between any two lines. Similar experiments can be carried out on the grid transformer for a single-phase load on the star-connected secondary side.

**Phase Change** of three-phase transformers can also be studied with the PSS1.
GRID TRANSFORMER DIFFERENTIAL PROTECTION

The PSS1 allows investigations can be carried out in the applications of differential protection. These include, but are not restricted to:

- Phase Fault Settings
- Earth Faults on the Star Winding
- Restricted Earth Fault Protection

SUMMARY

The above experiments are only a sample of the capability of the Power Systems Trainer in the context of Transformation. The flexible design of the PSS1 and PSS3 allows for a much wider range of experiments to be designed and performed, and thus it is ideally suited for further project work and research activities. As it covers all the key elements of a power system, from Generation to Utilisation, it has become a very powerful tool to be used in Scenario Based Learning, in both an academic environment as well as in an industrial/technical training context. Many customers around the world have benefitted greatly from the TecQuipment Power Systems range, whether it is to teach students the fundamental principles of electrical power, or to train the next generation of electrical power system engineers serving the needs of industry.

For further details of the TecQuipment Power Systems range, and to see how it could be of value to your institution, please feel free to contact our Sales Team who will be more than happy to discuss your specific requirements.