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Randewijk, Peter Jan

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A NEW STATE OF THE ART MICROGRID LABORATORY SETUP FOR REMOTE, FLEXIBLE, HANDS-ON, EXPERIMENTATION IN POWER SYSTEM ENGINEERING

Peter Jan Randewijk
Technical University of Denmark – Centre for Bachelor of Engineering Studies
Ballerup, Denmark

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ABSTRACT
A brand new, state-of-the-art Microgrid Laboratory Setup was built at the Technical University of Denmark’s (DTU) Ballerup campus to aid with practical, hands-on teaching in the field of power system engineering. The primary focus of the Microgrid Setup is to closely emulate the behaviour of thermal power plants, e.g. emergency power plants, modern distributed combined cycle gas turbine (CCGT) and combined heat and power (CHP) plants, especially with regard to synchronous generator control.

During the COVID-19 pandemic, an additional requirement came to the fore, in that this Microgrid Setup should also be fully accessible via the web. The design was broadened to include remote, hands-on and flexible experimentation [1], in order for student groups to engage in remote collaborative learning [2].

1 INTRODUCTION
1.1 The next generation power engineer
There has been a gradual shift from a small number of large power stations to a large number of smaller, distributed power plants in the recent year [3], [4]. The next generation power engineer [5] should not only have a detailed knowledge of the operation of the synchronous generators of these CCGT and CHP plants, but also on the operation of the typical state-of-the-art digital control equipment, different network protocols, supervisory control and data acquisition (SCADA) interfaces, etc.

The complexity in power system engineering has grown through the years [6], so that the next generation power engineer needs to become a “multi-disciplinary electrical engineer”. He/she is required to have a detail knowledge that ranges from electrical machines (including how the CCGT and CHP plants work), power electronics, power systems, grid stability, programming, digital networking and
protocols, telecommunication, control systems, to “legislative” knowledge of the Grid Code requirements [7].

1.2 The Microgrid Setup specifications

When the idea of a new Microgrid Setup at DTU first took shape, a literature study was first done on similar laboratories in existence [8], [9], and [10]. The next step was to try and see how a laboratory like this could best compliment the majority of power engineering courses at undergraduate level. The vast amount of microgrid laboratories focuses primarily on the integration of renewables, e.g. solar, wind as well as the inclusion of storage, either using batteries of fuel cells. These topics are however more specialised and assume a basic understanding of the operation of the “traditional” grid.

It was decided that the Microgrid Setup, as a starting point, should be more like a “micro” version of the “traditional” grid, in order to focus on the fundamental topics of power engineering, with undergraduate students the primary target group. These fundamental topics should include: synchronous machine excitation characteristics, synchronisation with the grid, automatic voltage regulation, the effect the load has on the frequency of the grid, how to control the amount of generated power using frequency droop control, the effect reactive power has on the voltage, voltage regulation by changing the excitation of the synchronous generator, the effect inertia have on the frequency, and the list goes on. It is also paramount that the Microgrid Setup should be fully digitally operated, with a digital network interface, emulating real world implementations and use the latest state-of-the-art technology available [5].

Denmark has seen a steady increase in the amount of smaller CCGT and CHP plants in the last few years, [4]. For Denmark’s transition toward a renewable energy future, these plants need to fulfil a somewhat different role than with traditional thermal power plants [11]. It is also of vital importance that power engineering students understand the traditional generation principles in order to fully appreciate the complexity of modern power system with a large amount of renewable penetration. E.g. droop control of power electronic frontends for renewables wind or solar installation, the need for virtual inertia, or short term energy storage etc. would then make much more sense.

2 METHODOLOGY

2.1 Bottom up design of the Microgrid Setup

The whole idea of the Microgrid Setup centred around three old København Titan motor-generator (MG) sets that was found in the university’s basement – two of them with flywheels attached – which was destined to be scrapped. These MG sets made use of shunt DC motors from the late 1960s. We decided to scrap only the shunt DC
motors and replace them with three-phase induction motors, whilst still keeping the old three-phase, salient four pole synchronous generators, as shown in Figure 1.

![Image](image-url)

**Figure 1** – The three old (red) three-phase synchronous machines connect to three new (blue) three-phase induction machines.

With the prime focus of emulating a microgrid with diesel – or CCGT “power plants”, this could be “easily” be done as in [12], using three-phase induction machines as prime movers, together with programmable logic controllers (PLCs) controlling three-phase frequency converters. This would create a more flexible experimental resource, ideally suited for flexible engineering education, [2]. The task of creating a diesel – or CCGT emulator, would also make for an interesting, even possibly a yearly recurring, collaborative design-built project.

The next step was to decide how these synchronous machines or “power plants” should be connected together to allow for maximum flexibility. A schematic diagram of how the experimental Microgrid Setup was configured, is shown in Figure 2.

Control cabinet +A1 (blue dashed rectangle) is responsible for connecting all of the synchronous machines together and if required, also to an external grid, or “infinite bus”. For later expansion, control cabinet +A1 would also be responsible for the connection of solar and/or wind power emulators to the Microgrid. Room in the cabinet has also been reserved for equivalent pi (π)-models for the transmission line or cabling between the synchronous machines’ – and the external grid’s busbars, as can be seen in Figure 3 (a).
Control panels +A2…4 (the other three dashed rectangles) are used for the control equipment for each synchronous machine. In order to increase the flexibility of the microgrid, it was decided to equip these control cabinets with a bi-directional ABB ACS800 inverter (as two 11 kW units were already available) to drive the three-phase inductions machines. This would make it possible for the three-phase synchronous machines to work either as generators, or as motors. The 50% over size is ideal for fast ramp-up and ramp-down times. The layout of control cabinets +A2…4 is shown in Figure 3 (b), with the bi-directional inverter shown in the middle, left of the picture.

The advantage of having a synchronous machine operating as a motor, is that it is very easy to change the power factor (PF) at which the motor is operating. The motor can thus even operate at a leading PF. Also, by having one synchronous machine operating as a motor, and the other two as generators, the effect of increasing or decreasing the electrical load in the grid, and how this increase or decrease of generated power is shared by the connected synchronous generators (when not connected to the infinite bus), can easy be demonstrated. Different frequency-droop characteristics can thus be implemented in order to study the effect of load sharing, and/or frequency restoration in the grid.
2.2 State-of-the-Art Synchronous Machine Excitation System

In order to ensure that the Microgrid Setup makes use of the latest state-of-the-art, small distributed power plant technology, we called upon the expertise of Burmeister & Wain Scandinavian Contractors A/S (BWSC). They have commissioned more than 180 power plants to 54 countries worldwide, with the latest power plant, the 56 MW North Power Station in Bermuda, which was handed over in a virtual certificate signing, due to COVID-19, on 31 March 2020, see Figure 4.

For the Microgrid Setup is was decided to make use of the ABB Unitrol 1020 excitation system\(^1\), exactly the same as was used in the North Power Station. The Unitrol 1020 includes, among others, a built-in Automatic Voltage Regulator (AVR), a Constant Power Factor (PF) control mode, a constant reactive power or VAr (volt-ampere reactive) control mode, automatic synchronisation, black-start or dead-bus synchronisation as well as a fully functional IEEE Std. 421.5-1995 type 2A/2B/2C Power System Stabiliser (PSS). With the PSS functionally, the Microgrid Setup could thus be used to supplement courses in Power System Stability, where it should be able to demonstrate local/inter-plant mode oscillations (in the 1 to 2 Hz range) and remote/inter-area mode oscillations (in the 0.2 to 0.8 Hz – with sufficient impedances between the generator busses) in the power system.

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The deciding factor however, was the CMT1000 LabVIEW based configuration and monitoring software program provided by ABB. This software is primarily meant to be used to configure ABB Unitrol 10xx excitation systems during commissioning. The CMT1000 software provides excellent blended learning opportunities [13] not only to supplement teaching in power systems courses but also in control systems courses, as well as for teaching Modbus TCP network communication.

For power engineering students the CMT1000 software provides a virtual software synchronoscope functionality as shown in Figure 5 (a). It is also able to show the operation point of the synchronous machine on the PQ capability diagram, as is shown in Figure 5 (b).

![Figure 5](a) The ABB CMT1000 virtual software synchronoscope (b) Operation point on the PQ capability diagram.

It is furthermore vital that power engineering students should be very familiar with MAC addresses, IP addresses, Subnet masks, Gateways, NTP server, etc. They

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also need to be familiar with the programming of digital network interfaces equipment. The Unitrol 1020 has a Modbus TCP interface which is one of the easiest protocols to implement from first principles on a PLC in one of the IEC 61131-3 languages, e.g. Structured Text. The CMT1000 software is able to display Modbus register data, Modbus request for a specific registers, together with the Modbus function codes, and the data transmitted.

When teaching control systems to power engineering students, there is usually a limited number of practical control systems experiments available, specifically applicable to power systems. Most control systems experiments are thus either simple motor control or power electronic related. The ABB Unitrol 1020 for the Microgrid Setup, enables the power engineering students to adjust the proportional (P), integral (I) and derivative (D) parameters for a PID regulated AVR controller. The CMT1000 software even has a built-in AVR Tuning Assistant to help with the tuning of the PID parameters. The graphical user interface (GUI) to some of these features are shown in Figure 7.

![Figure 6 – (a) The CMT1000 interface for the AVR Tuning Assistant (b) Manual PID tuning interface for the AVR/Auto mode.](image)

### 2.3 Microgrid HMI/Web-Interface

Each control cabinet were fitted with touch-panel human machine interface (HMI). For control cabinet +A1, the HMI would be used to control the connection configuration of the Microgrid and also control whether the Microgrid is connected to an external grid, or whether it is operational in islanding mode. The HMIs for control cabinets +A2…4 should controls the frequency converter which in turn control the speed and/or torque reference for the induction machine, thereby controlling whether the induction machine operate as prime mover or as three-phase generator/load.
The HMIs for control cabinets +A2…4 should also have full control of the excitation of the three-phase synchronous machine, by means of the ABB Unitrols. The DC field excitation should be manually adjustable, but it must also be possible to place the Unitrols in Auto/AVR mode, or constant PF mode, or constant VAr mode. It should also be possible to control the synchronisation of the synchronous machine to the rest of the grid, either manually or automatically using the Unitrols’ built-in Auto Synchronisation Mode.

It was decided to make use of an ABB AC500-eCo PM556 PLC together with an ABB CP600 10” touch-panel for each control cabinet. These Linux based touch-panels have excellent user security features which limits access to different touch-panel screens/pages. This implies that different user names, e.g. “experiment1”, “experiment2”, etc. can be created that only grants access to the touch-panel screens/pages applicable to a specific screen that applies to e.g. a specific experiment. The CP600 also allows users access to web pages from a remote web browser running on either a computer, or a mobile device such as a tablet or smartphone. These web pages are HTML5 based which implies that no plug-in external software is needed to display information remotely.

The layout of the four control cabinets with the four touch-control panels is shown in Figure 8, whilst a web page running on one of the CP600’s web servers, accessed via Google Chrome is shown in Figure 9 (a). The CP600 control panels also has built-in Alarm Tables that can be displayed either on the touch-panel, or on a configured web interface.

Figure 7 – The four control cabinets +A1…4 for the Microgrid Setup showing the ABB CP600 touch-panel and ABB M2M Digital Analysers.

Figure 9 (b) shows the web page interface to one of the ABB M2M Digital Analysers used. The M2M allows for voltage, current, active- and reactive power, apparent
power, power factor, THD%, etc. to be measured. The M2M also has a very handy ‘Table’ option where all the measurements, for each phase, can be displayed in table form via the web interface.

Figure 8 – Graphical User Interface (GUI) via a web browser for the touch-panel (a) and the digital power analyser (b)

In general, to quote from [2], “Remote monitoring, testing, and control are becoming increasingly important in manufacturing, process control, and customer support.” The web-interface of the Microgrid Setup not only support this subject matter, but also makes it possible for Web-based experimentation to supplement the theory with practical, hands-on activities in engineering education.

3 RESULTS

Although the Microgrid Setup has not yet implemented all the intended specifications as mentioned above, it was still possible to perform a range of remote, hands-on, lab experiments during the COVID-19 lockdown period. For the course 62761 – Power Engineering II, the class was divided into seven groups, and the remote experiments was performed in three separate sessions to accommodate all seven groups. Detailed instructions on how to operate the web interface to the CP600 control panel and M2M power meters, as well as the extent of the experiments to be performed was distributed to the students beforehand, as well as briefly demonstrated in a Microsoft Teams on-line lecture.

Each of the on-line Microsoft Teams lab sessions started where all the groups (a maximum of three at a time) were given a re-cap of the operating instructions for the on-line interface, as well as the various on-line experiments to be performed. The groups where then split into three sub Teams meetings. The instructor were able to remotely monitor the different groups’ control panels and M2M power meters continuously on his second 21” monitor. If he observed that one group was struggling, he could pop into their sub-meeting to clear up the problem, whether the issue was with the web-interface, or with some fundamental theory. The groups
could also use Teams Chat function to send the instructor a question, or ask him to join their sub Teams meeting, in order to explain something for them.

If the instructor saw that there was a common mistake, he could ask all groups to go to the main Teams meeting, while putting their sub Teams meetings on hold, where the common problem could be discussed. The instructor also cyclically popped into each sub meeting to comment on each groups progress, point out some interesting observations, etc. Although it was possible for the instructor to override some controls from his side, it never was necessary.

For this first remote, hands-on experimentation, the following online experiments were performed: (a) determine the open and short-circuit magnetisation curves of the synchronous machines; (b) synchronise the synchronous machine with the infinite bus; once synchronised, (c) operate the synchronous machine as synchronous condenser and a synchronous “reactor”; (d) operate the synchronous machine as an under excited and an over excited motor; and finally, (e) operate the synchronous machine as a under excited and over excited generator.

For each of these experiments, a number of current, voltage, power, etc. measurements needed to be documented, for use in additional calculations for the lab report. In the lab report the groups had to determine the saturated and unsaturated q-axis synchronous reactances. As it was impossible to measure the d-axis synchronous reactance online, this reactance value was given as a percentage of the q-axis reactance. With the q- and d-axes reactances calculated, the groups had to draw the six phasor diagrams for six different operating conditions, calculate the internal induced excitation voltage and power angle, and verify their active- and reactive power measurements with calculated values from their phasor diagram values for each operating mode.

From the seven groups, five groups scored above average grades (between 10 and 12 on the Danish scoring system), whilst two groups scored a 2 (just pass). This low score was not as a result of the on-line measurements, but had to with a fundamental misunderstanding of line-to-line, and line-to-ground measurements, as well as how to draw the phasor diagram of a salient-pole synchronous machine.

In general, the feedback from the students where quite positive, with the only comment from them that it would have been nice to have seen and heard the machines whilst doing the experiments. It was subsequently found that the CP600 touch panels has built-in support for a number of web cameras. Initial testing with a D-Link DCS-932LB web camera has shown promising results for video only integration into the CP600 touch panels and web server interface. In order to access the audio capabilities however, the web camera have to be accessed via the legacy Internet Explorer however.
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