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Title	Development and operation of a power take off rig for ocean energy research and testing
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Publication date	2011-01
Original Citation	Rea, J., Kelly, J., Alcorn, R and O'Sullivan, D. (2011) 'Development and operation of a power take off rig for ocean energy research and testing', 9th European Wave and Tidal Energy Conference, University of Southhampton, UK, 5-9 September.
Type of publication	Article (non peer-reviewed)
Link to publisher's version	http://www.ewtec.org/
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Download date	2026-10-05 11:05:10
Item downloaded from	https://hdl.handle.net/10468/2731

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Development and Operation of a Power Take Off Rig for Ocean Energy Research and Testing

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***Abstract*—Best practice for the development and testing of ocean energy converters generally follows a scaled approach. An important stage in this protocol is laboratory scale testing of power take off equipment, control, and grid integration. This requires test and control equipment operating at power levels corresponding to scales around 1:3-1:4 in order to match with typical scales for initial power take off testing at sea. This paper describes the design, development, and operation of such a system. Detailed information on the hardware components and supervisory control algorithm is presented. Flexibility, programmability, safety and robustness are particular requirements, and the design philosophy to achieve such is detailed.**

***Keywords*— Ocean energy, test rig, scaled testing, power take off, electrical power system**

I. INTRODUCTION

The development of ocean energy technology is steadily approaching the point where a significant number of full scale prototype deployments will occur. It is envisaged that by 2015 there will be several grid connected pre-commercial pilot plants and small arrays in operation, apart from those already in existence. This can be seen as an indicator that the fundamentals of device hydrodynamic designs and power take-off (PTO) operation principles are converging to some level of maturity, albeit there is still a relatively wide range of device types being considered.

Given these facts, and the imminent requirement to grid connect offshore devices and arrays, research and development focus has been sharpening on the control and performance of the electrical components in the power train, including generators , power converters , and grid interface equipment. Assessing design performance for these components under the operating conditions experienced in an ocean energy system is an expensive and difficult process, and to some extent can only be evaluated in real sea conditions. Simulations using software packages such as Simulink SimPowerSystems or DigSilent PowerFactory will result in outline specification and performance data, however some aspects of the electrical system are inherently intractable or complex to model. These include:

- effects of parasitic inductances and capacitances
- harmonics and electromagnetic interference
- thermal and electromechanical stresses
- transient thermal performance
- controller robustness
- supervisory control reliability
- component lifetime impacts

Most of these aspects are critical to successful long-term, reliable operation of an offshore system, and require actual experimental testing.

A complementary tool to simulation and actual offshore testing is in-house or laboratory physical testing utilising a scaled experimental test rig, that incorporates similar equipment to that being used in the offshore system. This has the advantage of being significantly less costly than offshore testing, and of being a controlled environment for baseline testing of the equipment or control system being utilised in the offshore environment. Moreover, the on-shore equipment can be tested in combination with offshore data, but over a wider range of conditions, and thus yield a fuller picture of the system characteristics. This approach is illustrated in Figure 1.

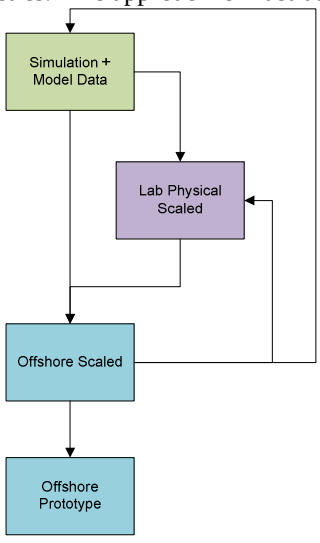

Figure 1 Process flow for electrical equipment testing

A recent research initiative has been undertaken at the Hydraulics and Maritime Research Centre (HMRC) in Cork Ireland in which such an experimental test rig was designed and constructed. The test rig is capable of recreating within a laboratory setting the dynamic response exhibited by a prime

mover onto a motor – generator set and simultaneously measuring the exported power level and power quality. The prime mover can simulate from real or modelled time series data any varying source such as a wind turbine, a hydraulic motor or a wave energy air turbine. As HMRC is dedicated foremost to ocean energy research, the primary application around which the test rig has been designed is a wave energy converter. The test rig is an extremely flexible tool in that it enables the optimization of a wide range of energy converter systems under various conditions. It is also a very useful tool in that the functionality of the wave energy converter under study can be almost entirely predicted at nearly all levels from wave to wire before any lengthy and expensive on-site sea trials are to be performed.

II. Design Requirements

The design of such a highly configurable, grid connected, experimental rig presents a series of unique design challenges. Safety and industry-quality robustness must be combined with flexibility, adaptability to different user requirements, future-proofing, and programmability. Such a system is likely to be used both as a research tool by postgraduate students and as a test bench for commercial operators on a consultancy basis, and the differing requirements and capabilities of both must be borne in mind.

The core design requirements are thus safety, hardware configurability, control programme flexibility and high quality, high speed data acquisition capability.

The test rig was built to industrial safety and design standards by compliance with the list of standards shown in Table 1. The use of an industrial Programmable Logic Controller (PLC) system in combination with robust hardware and software interlocks and a comprehensive error monitoring strategy further enhanced the ruggedness and safe operation envelope of the system.

Item	Applicable standard
Electrical installation	ET 101[1]
Electrical equipment	CENELEC & CE Mark (where applicable)
Electromagnetic compatibility	EN 60801
Electrical protection	Minimum IP 2x generally and IP 4x on top surfaces. Custom Perspex covers all have the Touch Hazard symbol

Table 1 Electrical safety standards

The flexibility of the system was designed a priori through a multi-contactor arrangement that allows for a number of different generator, power converter and grid emulator configurations, which are described in more detail in the following sections. These configurations can be selected by means of a user-friendly graphical PC interface program. Furthermore, multiple time series input formats, prime mover models and control algorithms can be loaded into the PLC via the same user interface. Generally, high speed data logging can be a challenge in PLC systems which are normally tailored to slower process control applications. However, a recent product addition by Mitsubishi of a unique high speed data logger card, has made it possible to combine in this system the features of industrial robustness and high speed data acquisition.

III. System Description

The physical power take off rig consists of a flywheel, a 4 position gear box, two 22 kW electrical machines, and a 500 Nm torque transducer. The associated control system includes a Mitsubishi Q-Series PLC, three Leroy-Somer 22 kW motor drives, 12 three-phase contactors, a soft starter, 7 current transducers, 13 voltage transducers, 2 power transducers and a PC with a software human-machine interface (HMI) graphical control program. Also included in the overall system are several inductors and capacitors that can be used to emulate the impedance of a grid connection consisting of both overhead and underground (or underwater) power lines.

Figure 2 Test Rig and Control Room

A. *Power System Equipment*

The power system of the main body of the rig includes the two electrical machines, the three motor drives, and the grid emulator.

Of the two machines one is used to simulate the prime mover of an ocean energy device and the other is used as the system generator. The prime mover is a Leroy-Somer LSMV 180 LU, which is a 22kW, 3-phase, 4-pole, squirrel cage induction motor, configured in wye, with a line-line voltage of 400V, a maximum line current of 40.3A, and a rated torque of 144 Nm. The generator is a Leroy-Somer FLSB 225M4, which is a 22kW, 3-phase, 4-pole induction generator, with the stator configured in wye, a line-line voltage of 400V, and a maximum current of 47.5A. The generator is nearly identical electrically to the 'prime mover'; the exceptions are that the rotor is equipped with slip rings and that the maximum line current is higher due to the larger thermal mass of the machine. Access to the rotor windings allows the generator to be wired as a squirrel cage induction, doubly fed induction, variable rotor resistance induction, synchronous, or self excited induction generator depending on user preference.

The generator setting can be chosen via the HMI and is controlled via the multiple configurations of contactors within the electrical system. When the generator is connected directly to the grid, a soft-starter is used to slowly bring the generator up to synchronous speed while protecting the grid from any initial inrush currents associated with magnetisation and starting torques.

The three drives used in the system are all Leroy-Somer Unidrive SP 33: one to control the 'prime mover', and two connected in a 'back-to-back' configuration to control the generator, to convert the power from the generator from the control frequency needed to maintain the generator speed to the 50 Hz frequency synchronised with the grid.

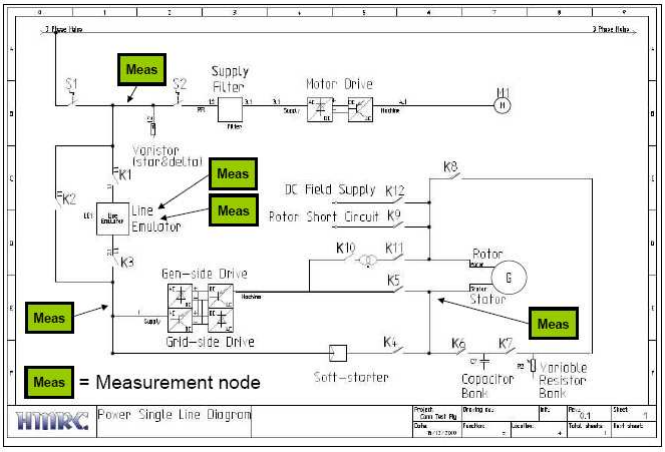

Figure 3 Power Flow Single Line Diagram

The grid emulator serves to re-create grid-like conditions at various connection points between the device and the AC network. The impedance networks within the line emulator were sized to simulate a cable distance of approximately 15 km of subsea cables and 10 km of overhead lines. The setup is analogous to an offshore generator situated approximately 25km from a strong grid connection point with various connection points in between. Each impedance network consists of inductor coils in series with each phase and capacitors in parallel with each phase. The impedance values are selected by scaling real values from typical cable and line specifications for a full scale prototype to the scale of the test rig. The measurement system is composed of 5 current transducers and 11 voltage transducers located at different points along the impedance networks. The current sensors have a nominal RMS current rating of 50 A and the voltage sensors are rated at 500 V RMS. Of the transducers located within the line emulator, three of the current and four of the voltage transducers output signals are monitored and stored by the PLC. The other two current transducers and eight voltage transducers measure instantaneous values of voltage and current and can be used for harmonics and other high frequency measurements. These are accessible and can be read by an external meter or monitoring device.

B. *Data Acquisition and Control Equipment*

The main control system for the rig resides within the Mitsubishi Q-Series PLC, which includes a Q04CPU, three analog input cards, one analog output card, two digital input and two digital output cards, two RTD input cards, a PROFIBUS card, and a high speed data logger card. The flow of data between the different devices within the system is illustrated in Figure 5. The analog input cards are used to collect all the data from the multiple transducers that are used to monitor the system. The analog output card is used as a backup communication path from the PLC to the three drives in the system. However, most of the communication between the drives and the PLC is performed via the PROFIBUS network.

The PROFIBUS network is used because it is reliable, robust, and allows for many more signals from the drive to be read/controlled by the PLC than would be feasible using only digital and analog communications between the drives and the PLC. The digital input and output cards are used mostly for control of the multiple contactors in the system, but are also used for control of a few display lights and signals to the drive including the "secure disable" signal in each drive.

The RTD cards are used to measure the temperature in the windings for each phase of both electrical machines for basic system protection purposes as well as monitoring the temperature profiles in the machines due to the non-standard power profiles seen in ocean energy devices.

The high speed data logger card monitors and records all required signals at the same rate as the PLC cycle scan time. This includes any sensor inputs, digital signals, and PROFIBUS signals, as well as inputs from the HMI and any other signals or program variables that the PLC programmer chooses to make available. This allows for detailed data analysis after the completion of any test. The data logger can be easily reconfigured depending on the needs of a given test. The data logger card has a specific advantage in that it is connected to the PLC system bus, and does not consume any communications bandwidth within the system. Information can be transmitted over the Ethernet to the PC HMI display at a much slower rate, purely for display purposes.

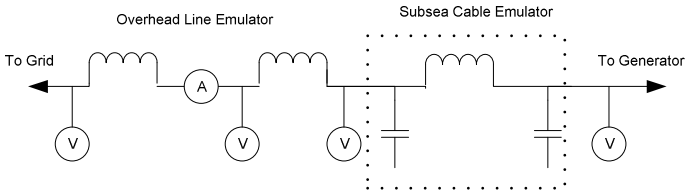

Figure 4 Single line diagram of the line emulator indicating voltage and current measurement points

There are a total of 39 signals from the transducers and sensors within the system. Of these, 29 are collected and monitored by the PLC, and 10 are available for more in-depth analysis if necessary. The 29 signals to the PLC include the twelve RMS voltage transducers, three true-RMS (i.e. high bandwidth) voltage transducers, three RMS current transducers, two true-RMS current transducers, one active

power transducer, one reactive power transducer, one torque transducer, and the six motor RTDs. The RMS voltage transducers are used to monitor the grid line-to-line voltage across each phase, as well as the line-to-line voltage across each phase on several nodes within the line emulator in order to monitor power losses and power quality over the emulated transmission lines. The three RMS current transducers monitor the current in each of the three phases in the line emulator. The line emulator structure and transducers are illustrated in Figure 4.

The three True-RMS voltage and two True-RMS current transducers are used to monitor the power output directly at the generator. True-RMS transducers are used because the voltage and current outputs of the generator are not guaranteed to be at a frequency of 50 Hz and will also contain high frequency switching noise, and the True-RMS transducers will give a more accurate reading of the voltage and current readings. The current transducers measure the current in phases 1 and 2; the current in phase 3 can then be calculated using vector sums, as shown below.

$$| I_3 | = \sqrt{(| I_1 |^2 + | I_2 |^2 - | I_1 || I_2 |)}$$

The torque transducer is used to measure the torsion forces between the generator and the 'prime mover'. The torque transducer is rated for a torque of up to 500 Nm and can measure torque in both directions.

In addition to these transducers that send data back to the PLC, there are eight voltage and two current transducers that measure the instantaneous voltages and currents along the line emulator at the same nodes as measured by the r.m.s. transducers. The difference with these sensors is that they represent the instantaneous values of voltage and current in the lines rather then the RMS value. Because of the nature of their signal, they are not compatible with the PLC. They have been added to the system to allow for more detailed analysis of the voltages and currents in terms of power quality or harmonics.

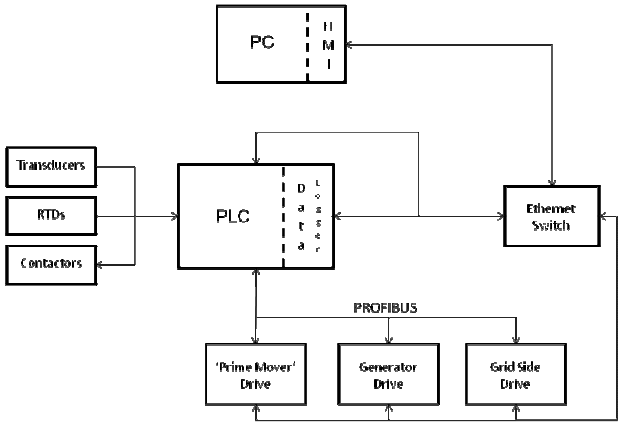

Figure 5 Control system communication diagram

C. *Mechanical Build*

The mechanical build of the drive train includes the generator, torque transducer, motor, gear box, and flywheel, and can be seen in Figure 6.The total inertia of the system, excluding the flywheel, is 1.25 kg·m^2. The inertia of the flywheel itself is 8 kg·m^2 and can be used along with the gear box to alter the total inertia of the system for testing purposes. The gear box ratios are 1:1, 1.576:1, 3.173:1, 5:1 and neutral, and these ratios are based on drive train to flywheel, i.e. at 5:1 the drive train will make 5 full rotations for every 1 full rotation of the flywheel. The purpose of the flywheel is to simulate energy storage that may be found in a real PTO device due to elements such as turbine inertia or designed flywheel storage.

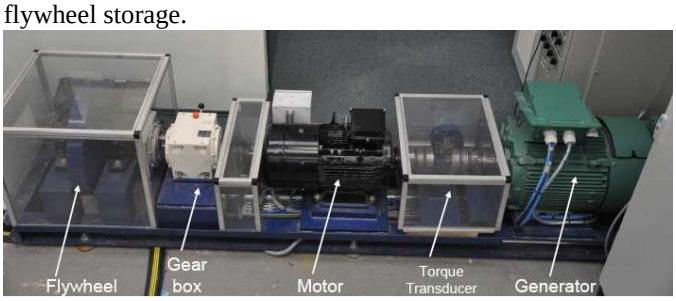

Figure 6 Drive Train

The motor drive, PLC, contactors, soft-starter and other electrical components are contained in the 1600mm wide motor drive panel. These are labelled in Figure 7. The other two drives are contained in the Regenerative panel, shown in Figure 8.

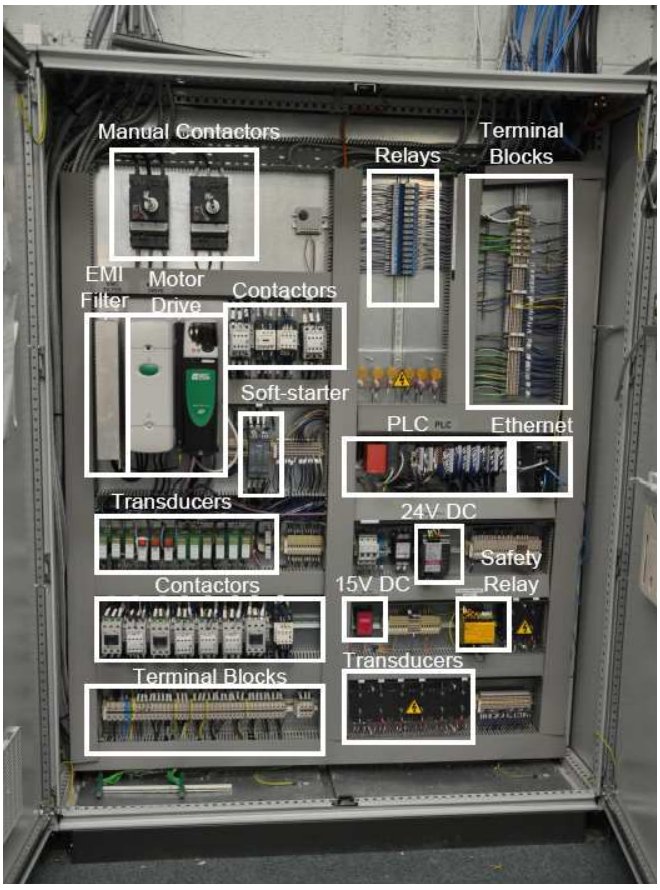

Figure 7 Motor drive panel

Figure 8 Regenerative Drive Panel

IV. System Operation

As described in Section II, robust, reliable system control in industrial applications is often achieved using a programmable logic controller (PLC), with user interaction controlled via a human machine interface (HMI). This section describes the operation of the PLC controller and the HMI.

In this application, as the PLC continuously scans the downloaded code it repeatedly performs the following four steps. Firstly, all the input signals from the analog and digital input cards are read, scaled and, where needed, filtered. This is followed by a safety check during which all system variables that have a bearing on system health are examined and checked. The majority of the autonomous intelligence of the PLC code is implemented in the subsequent step, the state machine, which is described below in more detail. Finally, output signals are scaled and written to the analog and digital output cards of the PLC.

A. *State machines – an introduction*

Pioneered in the 1960s by Moore[2] and Mealy [3], the state machine is a standard design approach in many fields of computer science and engineering used to define a process, programme or system[4],. A state machine is always in exactly one of a number of possible states and there are well-defined conditional transitions between these states. This application uses a Moore type state machine consisting of nine distinct states. The state machine is presented in Figure 9.

Once, in every scan cycle of the PLC, the state machine code is executed and the next state of the state machine is determined. Based on the combinational logic of both internal PLC generated status variables and instructions from the HMI the state machine will either move to a different state or remain in the current state for another scan cycle. The movement through the state machine, in normal, error free operation is described in the following paragraph.

B. *State machine - normal operation*

Every time the PLC is powered up, the state machine begins to run, always starting in its initial state called “Boot” and all variables in the system are reset to default values. After a predetermined period of time and if there are no errors, the state machine moves to the next state; “Idle”. In “Idle” the motor- , generator- and grid-side drives are all reset. Also, in “Idle” state, HMI instructions are read to determine the required generator configuration, the configuration of the transmission line emulator, the control mode of each drive, the spin up speed/torque and associated ramp rates. The system waits in “Idle” until the “start” instruction from the HMI user triggers advancing to the next state: “Spin up”. This state ensures safe sequencing when opening and closing the power-on and system configuration contactors and while enabling the three drives. This complex state comprises many sub routines, one of which is used for a given generator configuration and control strategy. An internal PLC signal indicates that all the spin up conditions have been reached and the state machine moves to the next state called “Spinning”.

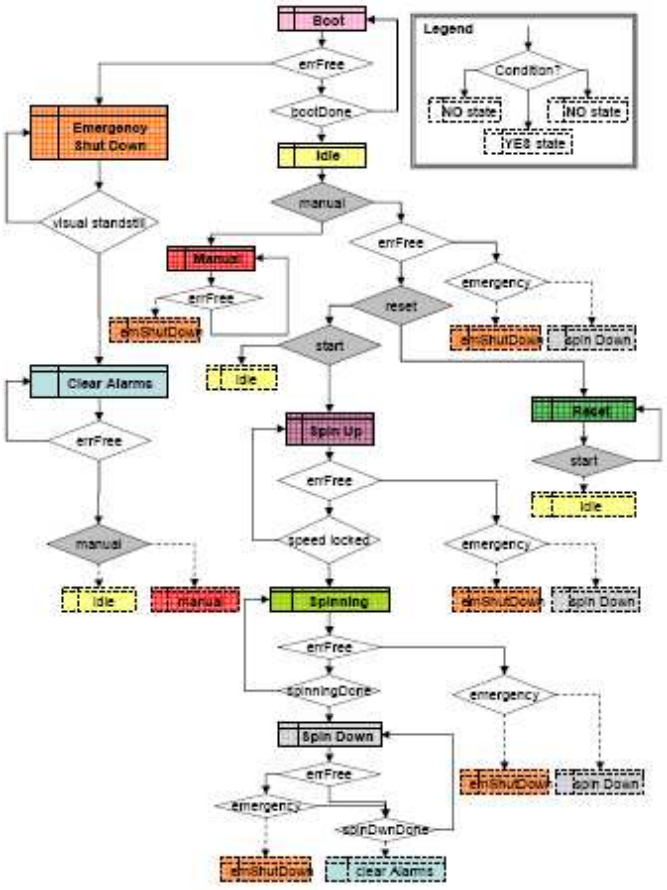

Figure 9 State machine - state diagram

In the previous state, “Spin Up”, the PLC took full control until both the configuration of physical system and the drives was safely completed and rotational speed had settled at the predetermined reference speed. While in “Spin Up”, any changes to speed and/or torque reference settings made in the HMI are ignored. In contrast, once the state machine reaches the “Spinning” state, the user can change any of the following input selections, and/or the parameters associated with them:

(i) Constant reference input
(ii) Sinusoidal reference input
(iii) File data reference input
(iv) File data reference input scaled by a real-time measured variable (e.g. power data file divided by real-time radian speed to give real-time torque reference data)
(v) Control Law algorithm

By restricting the user to only editing reference levels or control law parameters during the “Spinning” state, test flexibility and adaptability is preserved without sacrificing the safety offered by a spin up state, solely controlled by internal PLC values. The user is not permitted to alter either controlled machine parameter (i.e. speed or torque) or generator configuration during “Spinning” but rather must return to “Idle” make the desired alterations and move again through state “Spin up” to “Spinning”.

Once the user indicates that the test is complete or after a predetermined time period, the state machine moves to the next state, “Spin Down”. Similar to “Spin Up”, “Spin Down” comprises several sub-routines; the PLC selects the correct “spin down” sub-routine based on the control strategy and the generator configuration. The HMI displays the current state and the ten previous states. This display for normal operation of the state machine is show in Figure 10, where the oldest state is at the bottom.

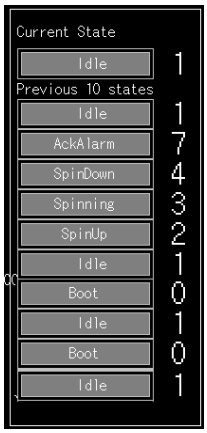

Figure 10 HMI screen shot of state log

C. *State machine – other states*

By describing normal error free operation, five of the nine state machine states have been discussed. The remaining four states are ‘Reset’, ‘Emergency Shut Down’, ‘Acknowledge Alarms’, and ‘Manual’. The ‘Reset’ state is reached using a HMI instruction when the state machine is in ‘Idle’. It resets all drives, all contactors and purges all results. Certain events can trigger alarms which cause the system to protect itself by powering down. These events are discussed in greater detail in a following section (section E) below. Some of these events require that the system shut down as quickly as possible and that all sources of power are disconnected from the system; this state is “Emergency Shut Down”. Following an emergency triggered shut down, the system waits for the user to confirm that the system is visually at standstill. This confirmation permits the state machine to move to the next state “Acknowledge Alarms”. In this state, the user can identify and acknowledge the alarm and the system returns to ‘Idle’ if the error source has been removed or rectified. The state labelled ‘Manual’ is password protected and gives very flexible access to many system variables. It not used by the average user but rather is intended for use by an expert-user during commissioning.

Table 2 summarises the nine states of the state machine described above.

State	**Description**
Boot	Initial start up state. All variables are reset
Idle	System is at standstill and awaiting both system configuration information and the ‘start-test’ instruction from the HMI
Spin Up	Fully controlled sequence which safely brings the system from standstill to a desired spin up speed. Sequence will vary depending on control strategy and generator configuration.
Spinning	The system is spinning and will respond to changes made by the user to reference signals.
Spin Down	Fully controlled sequence to spin down the rotational test rig. Contactors are only opened where necessary to achieve standstill, i.e. removing grid connection from a synchronous generator. Spin down is used in normal operation once testing is completed and in error situations where the error does not prohibit safe system control i.e. over temperature.
Reset	Returns both the hardware and software to a known state.
Emergency Shut Down	In the event of a critical error, e.g. speed encoder error, all contactors are opened and all three drives are disabled, thus no additional energy can be added to the system. Rotation will cease when the rotational energy has been dissipated by friction.
Acknowledge Alarms	Alarms (i.e. errors and warnings) can be safely acknowledged and reset to zero if/when determined safe to do so. Alarm history logs can be purged.
Manual	A very flexible state aimed at the expert user, used during commissioning and debug

Table 2 State machine state descriptions

D. *Alarm handling*

Any system variable that has a bearing on system health is examined during the safety check step of the scan cycle. If a variable is outside a desired range then an alarm is flagged. Alarms have been classified as having one of three different severity levels; warning, error or critical error. Other than recording the warning and displaying it on the HMI, no action is taken when a warning is flagged. In the event of a non-critical error, the state-machine assumes full system control, ignoring any further instructions from the HMI and safely brings the system to standstill in a controlled manner. However, if a serious error or fault is detected and it is deemed that full system control cannot be guaranteed then a critical error is flagged. A critical error results in an emergency shut down. All contactors are opened and all three drives are disabled, thus no additional energy can be added to the system. Rotation will cease when the rotational energy has been dissipated by friction

E. *Alarms*

Having described how the system responds to each of the three different alarm types (namely, warning, error and critical error), the events that trigger these alarms are now examined. These alarms can be considered in three groups, analog inputs, digital inputs and state machine generated errors.

Temperature is typically a slowly changing parameter, and current can change quite rapidly. Both cause damage if sustained at elevated levels for prolonged periods of time, but generally overlaod levels can be tolerated for short periods of time. These can often occur transiently, and may not be representative of a fault condition. Therefore, they are compared to multi-level thresholds which increase the level of response as the temperature or current increases. When the measured value exceeds the first threshold level (HI) a warning occurs. No further action is taken other than reporting the warning on the HMI screen. Exceeding the upper threshold (HIHI) causes a more serious response; an error is flagged and subsequently a controlled shutdown occurs. All voltage, power and torque measurements are compared to a single threshold (HIHI); any exceedance will trigger an error and a controlled shutdown.

If the speed signal is observed to be outside the operating range an error will trigger and a controlled shut down will be implemented. Certain generator configurations have restricted operating speed ranges, e.g. a direct grid connected synchronous generator. These operating ranges are automatically set by the state-machine for the “Spinning” state. If required, the user can also further restrict the allowed operating range. These PLC based speed checks are supplemented by the internal safety systems of the drives. Both the motor- and generator-side drives have internal over-speed and over-current limits, and any violation of these will cause the drive to trip. This digital input signal triggers a controlled shut down.

Another digital signal that triggers a controlled shut down is the fault signal from the soft-starter. (If the generator configuration does not use the soft-starter this alarm is de-rated from an error to a warning). The next group of digital signals indicate a fault in a critical piece of hardware, and any one of these will cause an emergency shut down. These signals are the three drive status signals, the status signal from the 24 V DC supply and the external emergency stop buttons. An emergency shut down will also be triggered if, after allowing time for switching, any contactor status (i.e. open/closed) is different from the instruction sent to that contactor.

In addition to the alarms generated by observing the analog and digital inputs, alarms are generated internally by the PLC. These alarms are generated if an invalid configuration is requested or if a state times out, e.g. if a controlled spin down takes longer than expected, an emergency shut down is triggered.

F. *Configuration contactors*

The flexibility to arrange the generator into any one of 11 different configurations is achieved by the nine contactors shown in Figure 11. Each of the 11 generator configurations is achieved by closing a particular combination of contactors as outlined in Table 3. These combinations are the only valid combinations that are permitted. All other combinations are either of no interest and/or potentially seriously dangerous to both equipment and people.

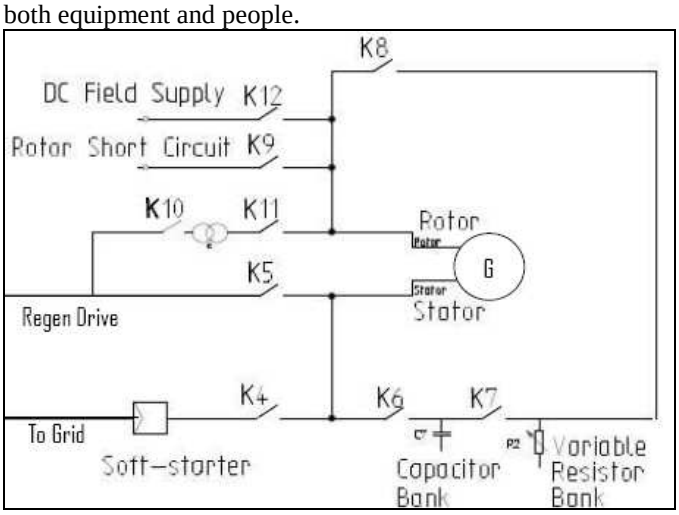

Figure 11 Generator and associated contactors

The different configurations described in Table 3 can be understood as follows:

- **Grid** : Direct grid connection, through soft starter
- **Regen** : Connected to grid through full rated regenerative power electronics converter
- **Sep Ex** : Separately excited, i.e. connected to a capacitor bank and resistor load to emulate an off-grid generator
- **Open** : Open Circuit, no connection
- **SCIG**: Rotor windings shorted to emulate a squirrel cage induction generator
- **WRIG** : Wound Rotor Induction Generator with resistance load on the rotor windings

- **SG(DC)** : DC Source connected to rotor windings to emulate a synchronous generator
- **DFIG** : Doubly fed induction generator, with rotor connected to the grid through a transformer and regenerative power electronics converter.

Configuration ID	**Stator**	**Rotor**	**Close :**
1	Grid	SCIG	K4 ,K9
2	Grid	WRIG	K4, K8
3	Grid	SG (DC)	K4, K12
4	Regen	SCIG	K5, K9
5	Regen	WRIG	K5, K8
6	Regen	SG (DC)	K5, K12
7	Sep Ex	SCIG	K6, K7, K10
8	Sep Ex	SG (DC)	K6, K7, K12
9	Grid	DFIG	K4, K10, K11
10	Grid	Open	K4
11	Open	Open	All open

Table 3 Generator configurations

Consider a generator configured as a SCIG and connected to the grid through the regenerative power converter, in speed control mode (K9,K5 closed). If then, K4 is somehow closed accidentally; the stator is driven by both the synchronous grid and the asynchronous output of the regenerative drive. This highly undesirable situation could result in damage to the regenerative drive and, since control of the rotating system is lost, mechanical damage to the drive train.

As the above example clearly illustrates, all invalid configurations must be avoided to ensure safe operation. This is achieved by two layers of protection; software interlocks and hardware interlocks. Contactors are closed by the PLC sending a 24 V DC 'close' command to the contactor input. Once the contactor has successfully closed, another 24 V DC signal is read by the PLC to indicate the 'closed' status. The PLC code is written to prevent invalid generator configuration requests by only allowing a contactor 'close' signal to be issued if the status of the other contactors indicate that it is safe to do so. This is the software interlocking.

An additional and fail-safe level of safety is offered by including hardware interlocking which is achieved by connecting the auxiliary outputs from appropriate contactors in series with the input of a given contactor. Consider a simple example of two contactors, K1 and K2 as shown in circuit (a) of Figure 12. When the 'close K1' switch is closed by the PLC, the K1 coil is activated and the three current carrying contactors are pulled closed. Since there is no interlocking circuit (a), K2 can also be closed in the same way, irrespective of the state of K1. Auxiliary contactors are introduced in circuit (b) of Figure 12. When K1 coil is energized, all the contactors (listed below the 0 V line in the diagram) change from their normal state (i.e. either normally open (NO) or normally closed (NC)). By connecting the normally closed (NC) auxiliary contact from K2 in series with the input of K1, as shown in circuit (b) of Figure 12, K1 becomes interlocked with K2. In this arrangement K1 can *only* be closed if K2 is open and similarly K2 requires K1 to be open before it can be closed.

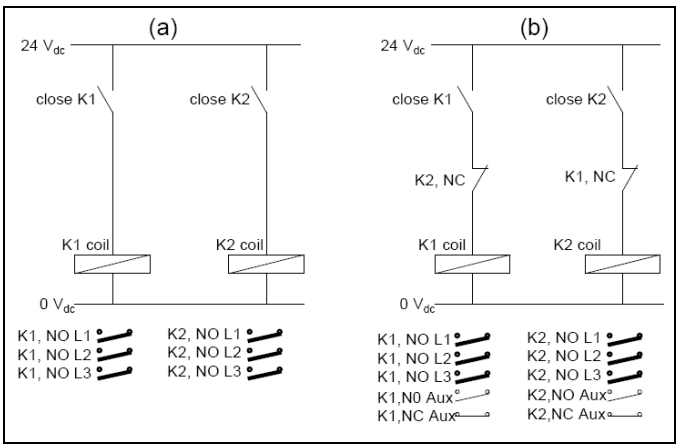

Figure 12 Interlocking, simple example

The specific interlocking requirements used in the test rig are listed in Table 4(refer to Figure 3 for a schematic of all of the contactor locations).

	Line Emulator Connections	
	Safety Condition	**Series connect**
K1	K2 must be open	K2 NC Aux
K2	K1 must be open K3 must be open	K1 NC Aux K2 NC Aux
K3	K2 must be open	K2 NC Aux
	Stator Connections	
	Safety Condition	**Series connect**
K4	K5 must be open K6 must be open K10 must be open K11 must be open	K5 NC Aux K6 NC Aux K10 NC Aux K11 NC Aux
K5	K4 must be open K6 must be open K10 must be open K11 must be open	K4 NC Aux K6 NC Aux K10 NC Aux K11 NC Aux
K6	K4 must be open K5 must be open K10 must be open K11 must be open	K4 NC Aux K5 NC Aux K10 NC Aux K11 NC Aux
	Rotor Connections	
	Safety Condition	**Series connect**
K8	K9 must be open K10 must be open K11 must be open K12 must be open	K9 NC Aux K10 NC Aux K11 NC Aux K12 NC Aux
K9	K8 must be open K10 must be open K11 must be open K12 must be open	K8 NC Aux K10 NC Aux K11 NC Aux K12 NC Aux

K10 and K11	K8 must be open K9 must be open K12 must be open	K8 NC Aux K9 NC Aux K12 NC Aux
K12	K8 must be open K9 must be open K10 must be open K11 must be open	K8 NC Aux K9 NC Aux K10 NC Aux K11 NC Aux
	RC Connections	
	Safety Condition	**Series connect**
K7	K8 must be open	K8 NC Aux

Table 4 Table of interlocking contactors

G. *Test operation*

In a research facility like the HMRC there is a frequent need to demonstrate the test equipment to visiting academics, industry representatives, governmental and state-body representatives, under- and post-graduate students. Therefore, the HMI for the rotational test-rig includes a demonstration mode which can be safely used by anyone in the test centre, even if their knowledge and/or experience in electrical systems is limited. A number of demonstrations are available, varying in duration and complexity. The second class of user who is catered for by the HMI is a researcher (e.g. internal HMRC staff researcher, external researcher or post-graduate student). This user has a good knowledge of machine theory and is focused on extracting data from a sequence of tests. The HMI/PLC has enough flexibility to run the required tests and gather the data in a suitable format. Alarm handling is well reported and easily understood by the user. There is no need for this user to have any understanding of the back-end of either the HMI or the PLC. The system is safe and will protect itself against any mistakes made by the user. The third class of user is expert in all areas of the hardware and software of the test-rig design and construction. The HMI provides this user with access to the 'nuts and bolts' of the PLC code while continuing to ensure that safety checks and alarm handling are carried out. In this mode, the HMI allows the expert user to mask any alarms that may be preventing a particular unusual test setup. This mode was widely used during the commissioning stage of the project and will be used in the future during re-commissioning of any replacement parts. Of the three HMI modes (demo mode, researcher mode, and expert-user mode) the researcher mode is the most commonly used.

H. *Experimental results*

The graphs in Figure 13 show the speed, the state of the state machine, and the current magnitude, active current and reactive current over time. The state of the state machine can be clearly seen moving from state 1, into states 2, 3, 4, 7 and back to 1, where state 1 is idle, 2 is spin up, 3 is spinning, 4 is spin down, and 7 is acknowledge alarms. The changes in speed can also clearly be seen in Figure 13ranging from 0 to 800 to 1200 RPM and then returning to 0 during spin down. The acceleration and deceleration rates can be seen here and can be adjusted by the user from the HMI if required. Also note the set point overshoot at the end of acceleration, this is caused by the speed control algorithm and can also be adjusted if necessary. Finally the graphs in Figure 13 also show the various currents in the drive during operation. The spikes in active current and current magnitude are directly related to the changes in speed, as extra torque is required to accelerate the motor which increases the current demand.

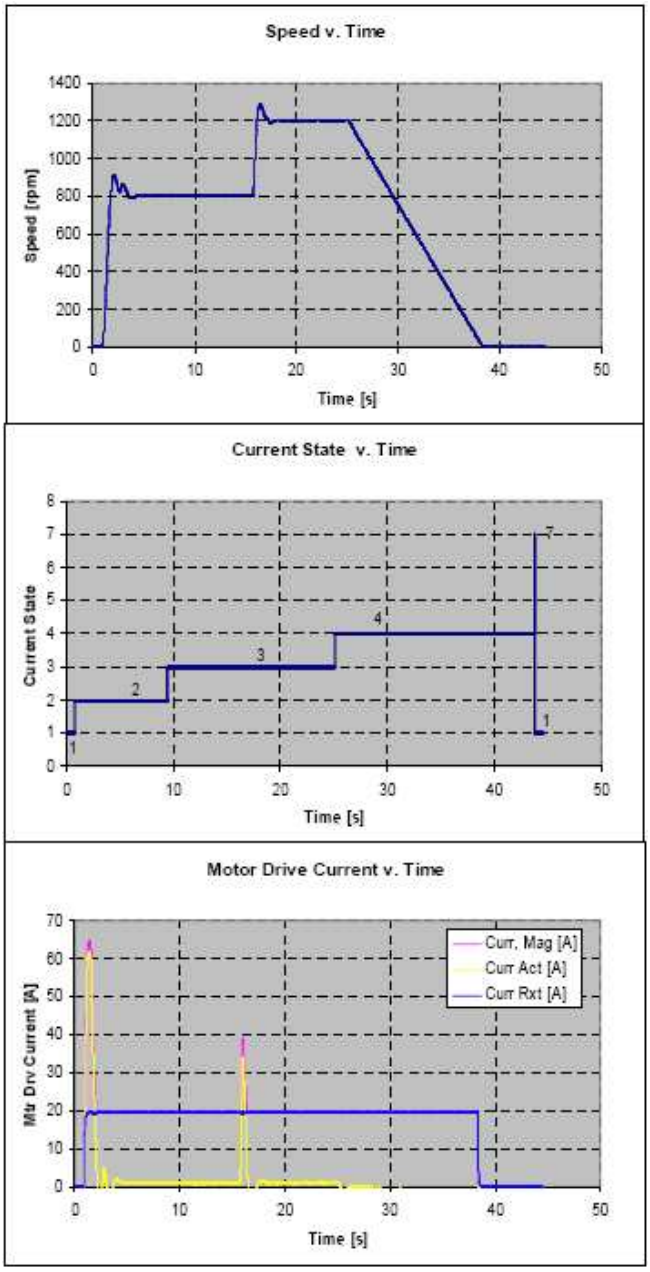

Figure 13 Speed, current state and motor drive current

In Figure 14, a zoomed view of the system speed and motor drive currents are shown. The resolution of these plots is of the order of 8 ms, illustrating the power of the high speed data acquisition system.

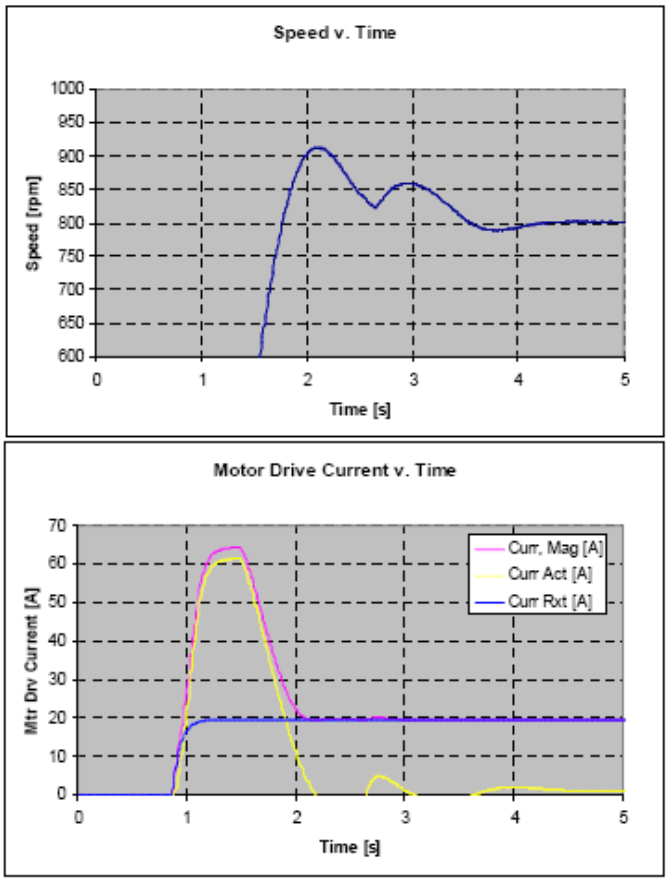

Figure 14 |Zoom in view of Figure 13

V. Summary

Scaled testing of power take off systems has been shown to represent an important stage in the development of ocean energy converters. This is particularly the case with respect to control algorithms, power quality, thermal performance, and load profiles on electrical machines and power converter equipment. For this testing scale to yield worthwhile results, power ratings must be in the order of 10-30kW. For best use of such a test system, flexibility and programmability is important. For safe use, particularly when grid connection is involved, the use of standard, certified, industrial quality equipment is vital. Moreover, best design practice must be utilised in operational supervisory control. This paper has presented such a system. A detailed equipment description has been provided for mechanical, power and control components. A leading edge PLC controller with high speed data acquisition capability built-in has been utilised as the intelligence backbone of the system. Coupled with hardware and software interlocking, a robust state machine control algorithm, and a sophisticated error handling protocol, this has resulted in a safe system that can be confidently used by both researchers and students. The selection of a wound rotor generator along with a multi-contactor configuration technique gives this system a unique level of flexibility in the selection of generator type. Some experimental results illustrating the operation of the state machine have been presented.

Acknowledgment

The authors wish to acknowledge financial support for this work from the Sustainable Energy Authority of Ireland and from Science Foundation Ireland through the Charles Parsons Initiative.

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