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Electrical Models of New Network Technologies and Devices Including Power Electronics and Supporting ICT Infrastructures

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About this report

The Institution of Engineering and Technology was commissioned by the Council of Science and Technology (CST) to research the emerging challenges for modelling electricity systems and how Britain's capabilities would need to be adapted to assess electricity system resilience as GB makes the transition to a low carbon electricity system.

This project commissioned, and received, fifteen individual papers from GB-based specialists of international standing in power system modelling. The authors of the papers worked with a wide stakeholder base of network companies, academics and others, who provided review and challenge. Professor Graham Ault CEng FIET was contracted to provide technical co-ordination and drafting. The emerging conclusions were further validated by means of an industry and academic workshop sponsored by Government Office for Science. The entire project was conducted under the direction of an independent steering committee composed of senior IET Fellows, two of whom were also CST nominees.

The report is composed of three parts:

- Part 1: Main report
- Part 2: Summary of Commissioned Papers
- Part 3: IET Special Interest Publication – Academic & Industry Papers

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EXECUTIVE SUMMARY

There are substantial fundamental differences between the characteristics of the electro-mechanical machines at the heart of a conventional power system and new technologies such as power electronic power converters and digital communication systems. The main differences concern the time-horizons over which the defining characteristics emerge but also in the fact that the control loops rather than physical parameters define the important characteristics and in the discrete-time nature of the systems. Modelling a future power system becomes a task of modelling a system of systems (electrical, electronic, communications etc.) and is a challenge faced in other sectors such as aerospace. The challenge is to create models of new sub-systems that capture sufficient detail to represent their features on the timescales of interest without burdening the computation with undue detail.

For steady-state and time-series sequential application of steady-state models, there are few difficulties. The challenges arise in modelling fast dynamic effects for various forms of stability and protection studies.

Detailed models based on underlying physics for checking performance in time domain are mostly in place. The principal remaining issue, and it is large, is whether convergence and agreement on control systems will be achieved between vendors and whether data to tune models/controllers will be available. The comparison is with, say, exciters for synchronous generators where the various types have been classified and typical ranges for time-constants and gains are known. There needs to be a major sector-wide and international effort to ensure that this is done for new technologies. Although raised here for transient (time-step) and steady-state models, this is a pervasive point. However, these detailed models used for verifying small sections of a grid are not appropriate for modelling large systems or long time scales.

A notable feature of modelling synchronous generators is that there is wide-spread (and well-founded) agreement on when the dynamics of various elements (damper windings, shaft compliance, exciter, PSS, governor) can be ignored as being too-fast or too-slow to be relevant to a particular type of study. We do not have that maturity of view for small-scale inverter interfaces or communication systems and arguably not for VSC HVDC. Possibly that is now in place for wind turbines, if not for aggregate wind farm models. Even so, there is a need to standardise the way that sub-system models are presented so that vendors can be asked to characterise their equipment in standard ways and they can be confident that in doing so they are not revealing detailed proprietary information about their implementation. This is an issue that has been addressed in other sectors and there maybe useful approaches for the energy networks sector to follow.

For the specific analysis of stability and protection there are some outstanding issues for models of power electronic equipment. For small-signal stability study, linearization of a complex and strongly non-linear physical system can be problematic and emerging power converter circuits take time to appear in commercial software in an appropriate form. There is also a lack of consensus on what level of detail or model order is appropriate. In large-signal studies (post-fault recovery etc.) there is a strong dependence on the control structure and signal-limit functions used by each vendor and a need to agree on standard ways to represent behaviour. In turn, the large-signal models need to be reduced to simple source-plus-impedance models for inclusion in fault flow algorithms. This is an immature topic and bedevilled by variation in control approach between vendors.

Even when the stability models of individual power electronic devices are settled there is still an issue of how to form aggregate models for use in large system studies which, with exception of perhaps wind turbines, is not well covered.

Power electronics is always a concern in the analysis of harmonics although not always for the right reasons. There is a large variety of harmonics emissions from nominally similar equipment and this makes forming aggregate models difficult. There is also an under-researched topic of the response of power electronic loads and sources to pre-existing distorted voltage (which can range from damping or anti-damping). For power electronic equipment, low-order harmonics are not the only, or even primary, concern. Current emissions in the kilohertz range are hard to assess both in terms of aggregate levels and impact on other equipment.

It is recognised that the engagement of consumers as active participants in the grid and the move from preventative to corrective grid control gives ICT technologies a central role and modelling of the combined control, communications and electrical systems is needed if one is to understand and quantify questions on operation methods, reliability or optimality of planned networks. This raises considerable issues on the scale of the model required but much more importantly issues of modelling disparate technologies in a holistic fashion. Modelling of communications systems is about event driven systems rather than continuous systems, it is also about quality-of-service rather than outage rates and efficiency. There are early attempts to co-simulate electrical networks and communications networks and explore their interdependence. However, we do not yet have a mature view of how quality of service as perceived by an electricity consumer is assessed from a co-simulation of communications and grid. It may be the case that the communications traffic associated with monitoring the grid and collecting metering data is modest compared with other telecoms traffic. However, the way in which aggregators will communicated with consumers (or their equipment) and the way in which data-mining will be used for indications of emerging behaviour are not clear and including this as part of a grid control feedback loop is beyond anything presently modelled.

1. BACKGROUND

Power electronics is firmly established as the means to efficiently condition power in industrial processes (such as variable speed pumps and servo drives), to interface non-synchronous generation (such as variable speed wind turbines and photovoltaic panels), as the crucial conversion stage between HVAC and HVDC transmission and as a source of reactive compensation in transmission (such as SVC and series compensators). We also see the early signs of power electronics being used to exercise control in distribution networks. The extent to which this technology has been modelled for use in power system studies is quite varied and to some extent it is still treated as an exotic technology to be modelled in a specialist study rather than as a mainstream power system element.

It is also clear that regardless of whether various control functions are centralised or distributed, sensor data will need to be brought to control processors and control actions will need to be communicated to control devices.

One cannot assess the efficacy of a control action, in a planning or operational context, without modelling the characteristic of the communications channels and how they influence the control.

In many ways, the history of development of the AC power system is the history of the synchronous machine and the characteristics of this machine have influenced the development of many other aspects of the system. For instance, protection schemes rely on the short-term over current rating of an electrical machine (available because of its large thermal mass) to provide the fault current necessary to discriminate faults. In turn, the required clearance times for faults are dictated by the over-swing and loss of synchronism characteristics of synchronous machines. On the other hand, electronic power converters are well established in the fields of OEM power supplies and industrial drives but have not influenced the development of traditional power systems. Electronic power converters have very different characteristics to those of electrical machines and would have directed engineers toward very different transmission and distribution systems.

In brief, the characteristics of electrical machines are:

1. They operate as voltage sources whose amplitude can be adjusted. The adjustment is normally part of a closed-loop excitation control scheme with a relatively low bandwidth.
2. Sine-wave voltage is a feature designed into the construction of the machine. The total harmonic distortion (THD) of the voltage is low. Distortion and imbalance in the load current will increase the distortion in the voltage to an extent dependent on the source impedance.
3. The short-circuit current is high because the source impedance is low and no current limiting is employed.
4. The current rating is set by temperature rise of the winding insulation. The thermal time-constant of the winding and surrounding steel is relatively large and a useful short-term rating is available. Fault currents of as much as 10 times the steady-state maximum can be sustained for several mains cycles.
5. Real power exchange is dictated by the torque applied to the shaft. Steady-state load sharing can be applied by a closed-loop governor setting that makes power output a function of the (common) system frequency. This is a designed in feature of the governor system but

it is similar to the natural tendency for the speed of the prime mover to droop when electrical load is drawn.

The corresponding characteristics of inverters are:

1. They operate as voltage sources (and in some cases current sources) with near instantaneous and independent control of the magnitude of each phase voltage.

2. Sine-wave voltage can be achieved through use of a suitable reference waveform and modulator but any shape can be used at will. Alternatively, closed-loop current regulation can be applied to achieve various current waveforms. The low-frequency spectrum of an inverter is well controlled but the switching action of the inverter produces high frequency distortion that can only be addressed through filtering.

3. Potential short-circuit current is high but protection against it must be provided in the form of current limiting action.

4. The current rating is set by the temperature rise of the semiconductors. The thermal time-constant of the semiconductor is very short and large over-currents cause device failure in considerably less than 1 ms. The cooling system also has a relatively short thermal time-constant and so even moderate over-currents can only be tolerated for short periods unless the inverter has been over-rated to accommodate them. Consequently little additional current is contributed in the event of network faults.

5. Real power exchange is dictated by the references applied to the control system (subject to the DC-link being able to source or sink this power).

It is the presence of fast-acting internal control loops, that in turn dominate the overall dynamics and characteristics of power converters, that gives rise to the major differences in modelling required for power electronic power converters over traditional rotating machines and transformers. The very different tolerance of overload conditions, the independence between phases and the presence of switching frequency distortion are also significant in some forms of analysis. The modelling challenges that arise are that (i) the modelling approaches used by the power electronics community are different to those of the power systems community and representing power electronics in a form that can integrate into standard software is not easy, (ii) the technology is less mature and therefore less converged between vendors than in other areas, (iii) propriety control approaches are common and have a large impact on performance and (iv) scaling models to different power ratings can involve non-obvious changes to control bandwidths and other crucial features which means that per unit scaling laws are not easily applied.

One can also identify some key differences between communication systems and electrical systems that make an integrated system-of-systems modelling a challenge, not the least of which is the discrete-time, packet-based nature of communications versus the continuous-time dynamics of most electrical phenomena. Indeed, there is a lot the power systems community may have to learn about systems engineering and systems modelling from other fields in order to rise to this challenge. Examples are to be found in modelling biological and medical systems.

The challenges presented for the various forms of power systems analysis can be summarised as these:

- Power Flow Analysis – power electronics converters do not always fit readily into constant-power / constant-current / constant-impedance view of the world but most cases can be incorporated into a power flow formulation as a power injection.

- Transient Analysis (time-step simulation) – power electronics community routinely use this but integration with power systems models is a challenge because of quite different time-steps required or the need to reduce the order of the power electronics models by neglecting some of the very fast dynamics. This needs care and verification especially where behaviour in abnormal conditions, notably fault response and recovery, is the focus.

- Small-Signal / Frequency-Domain Analysis – power converters can be represented in state-space form and linearised about operating point in a similar fashion to other equipment.

- Fault Current / Fault Flow Analysis – fault current from power converters is a function of how internal current limits are applied which is very different from a traditional "source-behind-an-impedance" view of generator fault current. Representation in impedance-plus-source form requires careful model reduction and verification.

- Harmonic Analysis – power electronic equipment can be responsible for low-order harmonic distortion and medium frequency emissions also. The large variety of implementations means that apparently similar devices can produce quite different emissions. Modelling the response of a converter to pre-existing network distortion needs careful understanding of the internal control structure and filter components.

For many of these types of analysis there is a need to keep the formulation simple and in keeping with the time-horizon of the study in order to keep the computational time reasonable. For modelling of traditional components this is well understood and the model choices accepted. For instance, in a synchronous generator model could include damper windings, main windings, shaft compliance, distributed masses, AVR (automatic voltage regulator), governor and PSS (power system stabiliser) and prime mover. One would not expect to see any one model include all of this. For a given study, some of these elements would be neglected as being too slow to have an impact or too fast to be of relevance; and each type of study would selected a different subset. In principle the same applies to an inverter-interfaced source which could include the switching frequency filter, current control loop, voltage control loop, droop controllers, DC link capacitor and DC sources. However, it is less obvious that there is a clean and reliable separation between time constants in all cases and less evidence of consensus on what to include for each study. In part this is because of the choices open to the equipment designers meaning that, for instance, the control bandwidth of the current controllers is not readily known with reference to a specific manufacturers product and even then it may not be divulged.

2. PROGRESS AND CHALLENGES IN MODELLING POWER ELECTRONICS

Although there is a lot of commonality between the circuits and control techniques used in power electronic converters for the various power systems uses (generator interfaces, HVDC, FACTS and load interfaces), it is apparent that the challenges for and maturity of models in the various use examples are different and so they will be described by use type.

2.1 Wind Turbine Generation Interfaces

The relative maturity of wind turbines and the present and expected levels of penetration in power systems means that modelling of the turbine interfaces, power converters and controls is well advanced and subject to continuing refinement and elaboration in industry and academia.

The dynamics of a multi-megawatt wind turbine involve different domains covered by different fields of engineering, including complex fluid and structural mechanics, electromechanical conversion and power electronics. Nevertheless, different phenomena take place at different time scales and certain components of the system have a decoupling effect which enables use of simplified models for some types of study.

The fundamental frequency of the tower bending modes in a 5MW wind turbine are in the range of 0.2-0.25 Hz, the blade flap-wise and edgewise modes are in the 0.8-1.1 Hz range and the blade torsional modes are in the 5-7 Hz range [1]. Dynamic simulations of these phenomena on single wind turbines are normally performed when designing wind turbine speed controllers using a combination of finite element method (FEM) structural models and blade-element momentum theory (BEM) aerodynamic models available in specialised software packages such as GH Bladed. Studies of the interactions between wind turbines due to wake effects, which have an effect on the overall WF power yield, can also be simulated using the BEM theory; however, when very detailed results are needed, computational fluid dynamic (CFD) models have to be solved using a super-computer and software packages such as ANSYS CFD or OpenFOA [2]. The mechanical system dynamics produce a decoupling effect and small high frequency disturbances are effectively filtered by the wind turbine rotor and the drive-train.

When doing power system integration studies, it is common to use a lumped-parameter model to represent the entire mechanical system. Such model consists of a series of masses connected by spring dampers with an external force applied on each end of the chain to represent the force exerted by the wind and the force exerted by the electrical generator. The two-mass model is widely regarded as a good approximation in most cases [3] [4].

The electrical generator and the transformer are normally simulated using lumpted-parameter models with constant parameters [5]. Such parameters are available in basic manufacturer datasheets and most software packages such as DIgSILENT PowerFactory, PSCAD or Matlab SimPowerSystems include generic values for them in their libraries.

On the other hand, simulations of generator short circuits, starting inrush currents, thermal transients and cogging torque at low speeds [6] may require varying the parametres of the model on-line or using FEM models. FEM models of electrical machines can be built using software packages such as Flux or ANSYS Maxwell; however, they require precise information about the geometry of the devices that is normally hard to obtain. When building large power-system models, it is convenient to reduce the number of state variables. A common approximation in electrical machines consists on neglecting the transients of the magnetising flux [7].

Wind turbine power converters use IGBT devices switching at frequencies between 1 and 5 kHz. Sub-switching time-scale simulations, in nano-second time steps, are used in the converter design stages as they can capture the semiconductor device dynamics. They are normally performed using specialised software such as Ltspice or Pspice, as they facilitate importing component-level parameters from semiconductor manufacturer data. Switching time-scale simulations including higher level controllers can capture the response of the converter to fast events such as close short circuits in the grid. They are done using general purpose simulation tools such as Matlab SimPowerSystems or PSCAD with simulation time-steps in the range of microseconds. Most wind turbine power converters use Pulse Width Modulation (PWM) to generate the switching signals of the IGBTs, this enables using the so-called averaged models where the alternating discrete states of the converter are approximated by an equivalent averaged system with continuous states [8]. This approximation is convenient as it enables using millisecond time steps to speed up the simulation. Averaged converter models are commonly used in Matlab SimPowerSystems, PSCAD and DigSilent for simulations in the range of tens of seconds.

The discussion so far has concerned modelling individual turbines. This is important for examination of detailed phenomena within a wind farm collection array and for interactions with, for instance, an HVDC link to shore but for many power system studies of load flows and system stability, modelling of aggregate behaviour of an array of turbines is needed.

For power flow studies, wind farms can be modelled as power injections (and in time series form for sequential load flows). Wind farm controllers and/or turning controllers that vary reactive power injection as part of a voltage regulation functions can do so by mimicking AVR droop settings and so can be accommodated readily.

In order to reduce the computational time required to make power system level simulations with a large number of wind turbines, aggregate wind farm models are normally used. These models neglect the differences between the collection grid impedances as if the collection grid had individual radial connections of the same length for each wind turbine. Akhmatov is widely acknowledged for a methodology that aggregates fixed-speed wind turbines according to the wind speed at their location **[9]**. The same principle is also used in later works for DFIG **[10]** and wind turbines with fully-rated power converters **[11]**. Validation data for these models is not easy to obtain but published work suggests that even with a single machine, aggregate models capture the relevant dynamics of the wind farm **[12]**.

It is worth noting that most of the work on aggregated models aims towards simulating electromagnetic transients caused by faults where the wind speed can be considered constant during the simulation. Therefore, the wake effect is only taken into account when calculating the pre-fault operating conditions using approximate methods in order to validate the level of aggregation of the model **[13]**. To date, no work has addressed a general validation of the aggregation level of a wind farm model considering all possible operating conditions.

Finally, current research on power-smoothing services suggests it will be economically-feasible for wind farms to provide a smoothed power output without additional energy storage means **[14] [15]**. This feature would simplify not only the operation of the power system but also the dynamic simulation of power systems as the wind farm would provide additional decoupling between wind speed variations and power exchanged with the grid.

2.2 DER Interfaces and Micro-grids

Inverters are used to interface many forms of distributed energy resource (DER) notably photo-voltaic arrays and battery energy storage units. Until recently their connection to the power system has been in modest numbers and at low powers and they have had little impact on overall system characteristics other than in terms of the energy they provide. In two regards that has obviously changed: the voltage rise observed with concentrations of PV and the magnification of frequency-dip events by disconnection of DER.

It is in the example of micro-grids where it has been necessary to develop models of inverter interfaces since DER often dominate over rotating machines in micro grids. For that reason, this discussion will make several references to micro-girds.

In terms of power flow studies the comments regarding wind turbines can be repeated and the inverters can be represented as power injections in most cases.

The application of stability analysis to micro-grid examples of inverter interfaces has been discussed [16] and the stability of an inverter-based system may be explored by following the framework established for conventional rotating plant. Rotor angle stability of a synchronous machine is comparable to the angle stability of a PLL (phase-locked loop) used to synchronise an inverter to a distribution network or to a power-versus-frequency droop function used to achieve governor-like power sharing of an inverter in a micro-grid application.

Frequency stability is comparable to the inverter maintaining the supply frequency when using a droop function. There is no spinning mass to limit the rate-of-change of frequency and instead it is the filtering included in the power measurement of the droop function that sets the low frequency dynamics and the frequency excursions.

Voltage stability is essentially the same consideration in both grid-connected and (islanded) micro-grid mode. In grid-connected mode, power injections will cause a voltage rise especially when there is load present. In a micro-grid application, the voltage depression during a fault or overload will be severe (because the inverters will enter a current-limit mode) and recovery from this voltage collapse must be ensured.

2.2.1 Small-signal analysis

Small-signal modelling and the ensuring of sufficient damping of power system oscillations is quite a specialised form of analysis although important in transmission system planning now and in future may well need to extend to distribution networks and the combined T+D systems of the future. To analyse the small-signal stability of a power system containing inverter-interfaced DG, linear models needs to be prepared for the inverters and merged with the rest of the system model. The eigenvalues of the combined system can be found and the damping of the various modes assessed. Both the power system and the inverters are strongly non-linear but the technique of linearisation is well-established. Linearisation is based on using the Jacobian matrices around a known operating point of the non-linear system to produce a state-space representation. Analysis by using eigenvalues is also well established and software packages such as Matlab have functions to calculate the eigenvalues from state-space matrices [17]. For micro-grid applications, work on small-signal stability has shown that the low-frequency modes are highly sensitive to the network configuration and the parameters of the power sharing controller in the inverter sources. Other examples (but not an exhaustive list) of small signal modelling are:

- A two-inverter micro-grid where a master inverter controls the AC voltage and a slave inverter is connected using a PQ controller [18].
- A large micro-grid which consists of a 69 bus radial system supplied by 20 generation units [19].
- A method of estimating the small-signal parameters based on perturbing the micro-grid [20].
- The use of an energy management system to optimise the micro-grid stability [21].
- Small signal micro-grid with an active load [22].
- Small signal model of a three-phase PV inverter [23].

There has been much work involving the small-signal stability of micro-grid applications. However, little effort has been directed to small-signal analysis of grid-coupled inverters, especially single-phase inverters (and indeed loads), as part of a whole-system analysis of systems where much of the inherent damping of traditional power systems (PSS on generators and resistive loads) has been displaced.

Tackling this problem would require identification and verification of ways in which aggregate behaviours of large numbers of small inverters could be represented with a sufficiently accurate view of dynamics and damping without an explosion in order of the model. Model orders for transmission studies can already run to 1,000s and 10,000s and in future could reach 1,000,000s.

2.2.2 Large-signal analysis

Large-signal analysis is used to evaluate stability in the presence of large disturbance for which linearised models are no valid. Little work has been conducted on the large-signal analysis of micro-grids. This typically involves the use of software simulation packages for example PSCAD/EMTDC [24]. Transient stability of a micro-grid may be analysed by using a Lyapunov function [25]. For grid connected applications, analysis of the transient stability of an inverter interfaced generator connected to an infinite bus has been achieved by representing the circuit components of an inverter as impedances [26]. The result of this is compared to models of synchronous machines. There are gaps in the literature about the transient stability of, and the tools to analyse, single phase inverter generation in distribution networks. Since most inverter-interfaced generation within the UK distribution networks is single-phase, this is an important topic area for the UK distribution network.

2.2.3 Fault models of inverters

It is well known that the output current of an inverter should be limited to avoid damage to the semiconductors. As a protective measure, practical inverter applications may disconnect the inverter when a short-circuit current is detected in the inverter. Controllers have been developed [27]-[33] to allow inverters to supply a fault-current. This ensures that the output current does not exceed the rating of the inverter. The software (controller) limit allows the inverter to remain connected for the duration of the fault. When using a software current limiting method, the fault-current of an inverter is determined by its controller [34]. Some academic work has sought to represent the fault current limiting behaviour in a format compatible with traditional fault flow studies [35] [36], but this is not widely done and not established in the sorts of commercially available software tools used by system planners. As penetrations of such inverters rise, this will become a necessity to preserve the integrity of the protection system.

Ride-through of voltage dips, and more broadly fault-ride through is an acknowledged issue. There is a large variety of approaches that may be taken inside an inverter to achieving this and characterising the outcome in general terms is not straightforward. There have been empirical studies of behaviour of commercial inverters [37] and some academic studies of the relation between control structure and fault ride-through [38] and of how tripping of DG can cause local voltage collapse [39]. This issues is less well characterised for small single-phase inverters than for larger three-phase inverters (and in particular wind turbines).

2.3 HVDC

Current-source converter (CSC) and early (i.e., 2- and 3-level) voltage-source converter (VSC) HVDC are well-represented in commercial modelling software in general. There are residual difficulties in, for instance, modelling small-signal disturbances in some packages where support for power electronics can be poor. Fault current models might also be rare. CSCs do not provide AC-side fault current, and indeed suffers commutation failure under AC voltage dips so would be disregarded for a fault flow study and for a transient stability study their recovery time from commutation failure / blocking would need to be modelled. VSCs offer a small amount of AC-side fault current (between 1 and 2 pu current), but can ride-through voltage dips. Their fault current contribution is presently ignored as a minor feature of overall system. However, if and when protection strategies are evolved to cope with low fault current environments of network regions with a low short-circuit current ratio (SCR), it will be necessary to more accurately represent even small fault current contributions.

Modular Multilevel Converters (MMC) [40] have become VSC of choice and VSC in general are encroaching on the territory of CSC in that their ratings are increasing, the power losses approaching those of CSC and the cost reducing. They offer a greater degree of control flexibility, a smaller footprint, an ability to work with weak networks and an ability to interconnect in DC grids. However, these converters are complex electrical systems which consist of numerous electrical modules (often in the form of stacks of H-bridge cells) and devices in addition to advanced control systems compared to the electrical and control minimalism of the classic 2-level or Neutral Point Clamped converters. More recently, other MMC-like converter topologies have emerged, consisting mainly in the hybridisation between the MMC and previously existing concepts. New topologies such as the Alternate Arm Converter (AAC) [41] [42], or other hybrids [43]-[45] often come with improved features over the classic MMC, such as DC-side fault blocking or reduced number of cells, but also involve even higher degrees of circuit complexity, hence further making their modelling harder. Finally, other topologies based on the MMC have also been proposed to extend the use of this AC/DC converter topology to DC/DC [46] [47], or AC/AC in Back-to-Back configurations [48]. Consequently, all these equivalent MMC models are even more challenging especially when higher levels of details are required.

2.3.1 Types of HVDC Converter Model

The Cigré Working Group B4-57 (WG) has been created to establish a classification of the different types of MMC models based on the modelled level of details. Table 1 presents the proposed classification into types 1-7 which are used in the following literature review. Most of these types trade off the level of details in the stacks of cells with the speed of computation.

This gain in speed is achieved by omitting the dynamics of the faster components in the electrical system, sometimes accompanied by large simplification steps in some parts of the control system, such as the low-level control of cells.

Type 1 is often dismissed when studying a converter topology as the dynamics of semiconductor devices often do not overlap with those of the converter by several order of time magnitude. For this reason, most of the development of new topology and the study of their transient and steady state behaviour is done using Type 2 or 3 models, often called Traditional Detailed Model (TDM). Type 3 is often preferred by default in the Electro-Magnetic Transient (EMT) simulation software as it offers similar results to Type 2 but with faster computation time. For example, the Detailed Equivalent Model (DEM) [49] is a Type 3 model with some optimization in the modelling of the equivalent resistive network, yielding an improvement of a factor 2-5 in the computation time depending on the original complexity of the MMC model while retaining excellent results accuracy when compared to the TDM [50].

Starting from Type 4, the H-bridge cells are being simplified. The Accelerated Model (AM) [51] looks at the Thevenin / Norton equivalent model of the cells and consequently the whole stack in order to obtain a much simplified electrical system.

When compared to the TDM and DEM, the accuracy in terms of arm current and stack voltage waveforms is again acceptable [52] and the simulation time gain is even more appreciable at around a factor 4-8 to the TDM.

In Type 5, the whole stack of cells is replaced by a controllable voltage source which includes differential equations to link the voltage and current waveforms of the stacks with their energy content, i.e. in its cell capacitors, and ultimately resulting in the update of their maximum voltage constraints. Several Average Value Models (AVM) of Type 5 exist for the MMC [53]-[55].

Such models have also been experimentally verified [56]-[58] with the results showing an overall good fit between the simulation models and the experimental data apart from the high frequency contents inherent to the dynamics of individual cells and rapid transients, e.g. DC-side faults. A Reduced Dynamic Model (RDM) of the AAC has also been suggested [59].

Type of model	Description	Simulation Tools
1 – Full Physics Based Models	Switches are represented by differential equations	Not suitable for grid models
2 – Full Detailed Models	Switches are modelled by a non-linear resistor	EMT
3 – Detailed Model	Switches represented by two-value resistors	EMT – faster than type 2 but loss of switching details
4 – Detailed Equivalent Circuit Models	Use Thevnin/ Norton equivalent to reduce the number of nodes	EMT – faster than type 3 but loss of device details
5 – Average Value Models (AVM) based on switching functions	AC and DC sides modelled as controlled current and voltage sources with harmonic content	EMT – faster than type 4 but loss of sub-system details
6 – Simplified Average Value Models	AC and DC sides modelled as ideal controlled current and voltage sources	EMT and phasor-domain – much faster but loss of converter internal details
7 – RMS Load-Flow Models	Load flow models will use steady-state converter outputs	Load flow – no transient details

Table 1: Classification of the types of MMC models.

Type 6 models simplify the MMC model even further by only looking at the AC and DC voltage contributions of the converter. This results in the removal of the stored energy aspect of the MMC [60], making the obtained model MMC even more similar to the 2-level VSC. In Type 7, the MMC is likely to behave exactly the same as any VSC since only steady state power flow are considered, thus defeating the point of developing purposely MMC model for this type of models.

Remarkably, in the fast transient of a DC-side fault, it has been shown that the MMC behaves similarly to an RLC equivalent circuit, at least during the first few milliseconds of the transient period before other devices start acting, such as DC circuit breakers [61]. Finally, Qingrui [62] demonstrated that there exists a minimum sampling frequency ($F_s = \pi\ n\ k_{mod}\ F_0$) below which the voltage steps in an MMC staircase waveform are not modelled accurately enough.

As a consequence, simulation models of the MMC based on Types 2-4 become inaccurate when the simulation time step is chosen greater than this specific limit and models based on types 5-6 should be preferred depending on the levels of details inside the converter still desired.

2.3.2 Availability of MMC models

To date, Matlab/Simulink and EMTP can simulate Type 2-6 models but are mostly used for Types 2-5 as other platforms are better suited for network studies. However, only the 2-level converter is readily available as a selectable item in their respective simulation libraries. Therefore MMC models must be built from scratch using passive and active components. Neither PScad nor DigSilent offer MMC models in their simulation libraries and their limited collection of passive and active components make these simulation platforms better suited for Type 5-7 simulation models.

Modelling an MMC up to Types 6-7 must include extensive control systems whose design and tuning process usually require experience advanced knowledge of control theory [63]. The use of more traditional Direct- and Quadrature-Axis (DQ) decomposition technique has been proven to be working but generally results in the creation of uncontrolled second harmonic current waveforms through the arms due to the combination of the small voltage fluctuations from the cell capacitors. Schemes such as the Circulating Current Suppressing Control (CCSC) [64] can be added to the control system in order to keep this undesired circulating current in check.

In summary, much effort is underway worldwide and models of VSCs for power systems studies are maturing rapidly. Although not everything one would wish for is present in the models today, the widespread recognition of the importance of topic in both the academic and commercial fields and the categorisation pursued by Cigré mean that there is probably sufficient effort already directed at this topic without the need to stimulate work further.

2.4 FACTS

With some sections of the transmission grid operating closer to its operational limits because of growing demand and restrictions on building new lines, there is a common consensus that the transmission grid needs to be upgraded and modernized to accommodate more renewable sources of generation. Flexible AC transmission (FACTS) devices can aid the network through enhanced controllability, improved stability and increased power transfer capability using existing AC transmission infrastructure. How these devices can be modelled and how they interact with the rest of the power system has been extensively studied. However, with the fast changing nature of power grids, there is an urgent need to rethink the planning and operational strategies, the availability of FACTS models to study different system phenomena's, validating the models and identifying gaps/limitations in software platforms.

2.4.1 FACTS device Models for Power System Planning and Operation

For FACTS devices to be included in transmission systems plans, there must be appropriate models for all the analyses that are normally performed. These analyses include those normally associated with system planning and system operation. The type of studies required include, but not limited to:

1. Planning (steady-state) considerations

- Economic justification for transmission network reinforcements versus FACTS [65].
- Optimal placement of FACTS devices [66] [67].
- Security Constraint Optimal Power Flow (SCOPF) studies performed by system planning to locate best siting of FACTS controllers that maximise their value [68].
- Reactive power dispatch [69].

2. Operational (dynamic) considerations

- Robust control for damping power system oscillation using FACTS [70].
- Transient stability improvement with FACTS devices [71].
- Subsynchronous control Interaction between wind farms and series compensated lines [72].
- Mitigation of sub synchronous interaction [73].

The table outlines system control functions that are most often considered when system planners evaluate when exploring the best available options for their networks.

Function	Non-FACTS solution	FACTS solution
Voltage Control	Generators Synchronous condensers Transformer tap-changer Shunt (series) Capacitor/Reactor	Static Var Compensator (SVC) Static Synchronous Compensator (STATCOM) Battery Energy Storage Systems (BESS)
Active/Reactive Power Flow Control	Generator Schedules Transmission line switching Series capacitor (switched/Fixed)	Thyristor controlled series compensator (TCSC) Static Synchronous Series Compensator (SSSC)
Transient Stability	Corrective Action (Special Protection Scheme) Braking Resistor	SVC, STATCOM, TCSC, BESS, SSSC
Dynamic Stability	Power System Stabilizer	SVC, STATCO, TCSC, BESS, SSSC

Table 2: FACTS and Non-FACTS Options for Various Control Functions.

2.4.2 Linearization of new technologies

Many important components in power systems such as generators and excitation systems, dynamic loads (e.g. induction motor), and power-electronics devices (i.e. FACTS/HVDC) have very non-linear characteristics and need to be linearised for small-signal stability analysis and subsequent design of damping controllers. The methodologies for obtaining a small-signal (linear) dynamic model of commonly used FACTS devices have been reported [74]. The dynamic behaviour of these devices is described thought a set of differential equations, whilst the power flow in the network is represented by a set of algebraic equations. This set of differential-algebraic equations is linearised with respect to an equilibrium point.

Linearization of large scale transmission networks with integrated power converter circuits (i.e. FACTS/HVDC and wind turbines) to obtain a state-space equivalence is a rather complex task due to the large number (often thousands) of system states. Low frequency oscillations in a power system are fairly linear when caused by small disturbances such as the random fluctuation of generation and load. The practical benefit of analysing such oscillations in the linear domain resides in the insights they provide into the dynamic characteristics of the power system; such insights are often not easily observable from nonlinear time domain simulations alone.

Since the 1996 blackout in Western Electricity Coordinating Council (WECC) system in the USA, there has been significant interest in measurement-based system monitoring to prevent a wide-spread system collapse [75]. For instance, in 2005, 2006, and 2008 the WECC conducted four system-wide tests of the western interconnected power system where probing signals were injected by modulating the control signal at the existing HVDC link. System-wide responses were observed from phasor measurement units (PMUs) across the system and off-line tools were then used to estimate the power system electromechanical modes [76]. These input-output measurement approaches have been an effective tool for estimating (identify) low-order linear state-space models of large scale transmission networks with embedded power electronic converter systems.

2.4.3 Tools to support system-level tuning and optimisation of, for instance damping

FACTS devices are installed in power systems to provide fast continuous control of power flow in the transmission system by controlling voltages at critical buses, by changing the impedance of transmission lines, or by controlling the phase angles between the ends of transmission lines in such a way that thermal limits are not exceeded, stability margins are increased, losses are minimized, contractual requirements fulfilled, etc. without violating the economic generation dispatch schedule. However, the sole presence of these devices does not improve the overall damping of the system appreciably. To ensure sufficient damping, supplementary control is required to be added to these FACTS devices. A number of approaches and techniques are utilised for the design (tuning/optimisation) of supplementary control for damping inter-area oscillations. One important aspect in the design and performance of the controllers is robustness. The controller should perform the desired function over the wide range of practical conditions encountered in the operation of the power system. The classical gain and phase compensation approach have been effective and widely used method for tuning and optimising power system controls [77].

However, modern power systems are typically multi-variable, i.e. comprising of numerous controllable devices (FACTS/HVDC, asynchronous/ synchronous machines) each with their own controllers.

Until recent years, the industry did not force a strict requirement on coordination among power system damping control. In light of system blackouts, the drive is more towards coordinated (and robust) control of the system. Properly designed controls for power electronics devices (i.e. FACTS/HVDC) will help ensure adequate security margins for a wide range of operating conditions, mitigate possible adverse interactions among controls, and enhance the overall controller performance. Tools for the development of coordinated control design of several FACTS/HVDC have received much attention in the past decades [78] [79] and the effect of controller interaction can be minimized by coordinated controller design [80] .

2.4.4 Modelling gaps in commercial tools

Models of power electronic elements of FACTS controllers and the converter stations of HVDC links are commonly available in commercial software packages but are typically 'black-box' models (that is, the works of the model are no revealed) that have been provided by equipment vendors. For example, General Electric provides their power electronics based models to National Grid in the DIgSILENT software platform for their system studies. Such black-box models are only really useful (and verified) for the specific case for which they are supplied and make it difficult to represent unusual situations or adapt for new use. In general, it takes time for the standard commercial software platforms to produce generic and open models of new technologies.

For UK transmission owners, DIgSILENT PowerFactory has emerged as the preferred software platform for carrying out system studies and the development of a roadmap for the future 2020 network and beyond. Alternative commercial tools such as PSS/E, PSCAD/EMTDC, EUROSTAG, and PSLF are also used for power electronics for power systems studies. However this software does also present their own limitations.

Often models suitable for time-domain simulation emerge first but frequency domain (small-signal) analysis plays an important role in analysing the stability of a power system. Although most of the commercial tools for dynamic studies are capable of linearizing the power system model for small-signal studies (that is, for eigen-analysis, mode-shapes, controllability / observability indexes), the tools are still not mature in providing a state-space representation of power systems with FACTS and HVDC elements and may not properly capture the dominant network dynamics and risk failing to properly design stabilising controllers for inter-area and sub-synchronous oscillations. Network operators are therefore limited to using trial and error methods for tuning system parameters. A method around this is to integrate models across different platforms such as interfacing DIgSILENT with PSCAD and then with Matlab. This allows first power electronic and power system models to be combined in time-domain simulations and then frequency domain models to be extracted. Through this route controllers can be tuned/synthesized in a systematic and analytical manner, but this is not a trivial undertaking [81] . In general there is a lack of tools to support tuning of a large number of stabilising controllers in a complex system.

2.5 Distribution FACTS

FACTS was imitated as a set of principles and techniques for transmission system support but most of the ideas have application in distribution systems also. The HubNet consortium has produced a position paper setting out that status of development in this area [82] . The overall status is that the technology is less mature than at transmission level because to date there has not been a strong drive to develop and deploy the technology but there is growing interest given the indications from the network plans of the UK DNOs that power electronic interventions in distribution networks may become necessary in the coming decade and evidence from the LCNF and NIC/NIA projects that demonstration of these technologies is underway.

The gaps in modelling for FACTS will apply to D-FACTS also. Any new forms of device developed for distribution use without a transmission counterpart, or where new control features are added to an established circuit topology, will require fresh modelling.

2.5.1 Soft Open Points

Soft Open Points are an example of distribution level power electronic network equipment. They have been assessed as a means to enable a greater penetration of distributed generation [83] [84]. The recently initiated LCNF project "Flexible Urban Network – LV" (sponsored by UK Power Networks) will trial this technology for relief of constrained feeders and substations.

This is a relatively new form of network reinforcement and as such does not feature in commercial tools to support network planning or operation. As with other forms of power electronic device, models will be required for power flow studies, protection studies and for planning tools.

2.6 Loads

Power electronics has come to dominate power conversion and conditioning in loads for reasons of optimising energy use or for tight regulation of supplies for electronic loads. As energy efficiency standards become more exacting for many classes of load we can expect to see more of the remaining direct-on-line motors being displaced by converter interfaced motor drives and resistive loads displaced by electronics (such as incandescent lamps replaced by LEDs). In power flow terms, the front-end rectifier will, by regulating its output voltage, present constant conditions to the load and thus present constant power demand to the grid. Modelling of constant power loads is well established and recognition is growing of the need to re-survey aggregate demand to assess the parameters of ZIP load models used to express sensitivity of power consumption to voltage as the CLASS [85] project has identified.

It is known that the damping provided by loads is strongly influential on power system oscillations and that the displacement of constant-impedance loads by constant-power loads will reduce damping and stability limits. Identifying load models for damping studies is a task to which one needs to repeatedly return.

Rectifiers divide into two main categories: line frequency and switch-mode with the former characterised by slow dynamics and low-order harmonic distortion and the later by fast control dynamics and high-frequency current emissions.

Models for a wide variety of line-frequency rectifiers are well-established but there are difficulties in determining what exactly is present in a load. For instance, the Low Carbon London project monitored several heat pump installations [86] and found a large range of levels of harmonic distortion between different types, between models from the same range and between identical installations operating to different duties. Modelling what one might expect in aggregate harmonics at a substation is not meaningful unless the degree of aggregation is large or worst-case estimates are used. There was also evidence that when sufficient numbers of distorting loads are present they may in aggregate cause excessive low-order harmonics even if each individual meets the relevant product standards.

Models for switch-mode rectifiers are available in much the same way as for DG-interfaces and with many of the same difficulties apparent. Two issues are deserving of greater scrutiny than they have received at present. First, in terms of waveform distortion, while the switch-mode rectifiers are largely free from low-order harmonic distortion, they emit high frequency currents at multiples of their switching frequency. In the range 2 kHz to 150 kHz, where product standards are absent and common EMC filters are, by design, intended to be effective, there can be large aggregate distortion on a feeder because many of the units of the similar type are present (such that their switching frequencies coincide). This problem has been acknowledged but is not routinely modelled. As the proportion of both loads and sources that have power electronic interfaces grows, it is likely that emissions in the 2 -150 kHz band will become more of a problem than traditional low order harmonics. This does not require whole-system models to be studies; it can be adequately assessed by looking at a selection of feeders. It is, however, an under-studied problem and worthy of study.

Second, the switch-mode rectifiers have internal nested current-control and voltage-control loops with significant dynamics that are often designed assuming supply will be from a stiff voltage source. These loops present the possibility of unplanned interactions when the supply is not stiff. This has been noted in micro-gird stability studies discussed above but will apply more widely. A particular instance is the harmonic current drawn by a switch-mode rectifier when it is presented with a harmonically distorted voltage supply. Many behaviours are possible: no harmonic current, current proportional to harmonic voltage and current proportional but with opposite phase.

This last case present negative harmonic damping and is of great concern. Representing the rectifier as an open circuit, harmonic damper or negative harmonic damper could be readily achieved; the difficulty lies in assessing the wide range of devices in existence.

The Top and Tail project [87] has set out to examine a number of technologies that could help relieve voltage constraints on low-voltage feeders. These techniques include voltage regulators at mid feeder positions, point-of-load (house entry) regulation; make reliance on the generous voltage input range of many modern power supplies to accommodate greater regulation and finally, conversion of “final mile” networks to DC. While this would ease the burden on voltage control in higher voltage networks it would cause a large fraction of the total load to appear as constant power loads.

Several of the disturbances to a traditional network rely on a contribution to damping from constant-impedance loads and this wholesale change to constant-power loads could have significance consequences for system-wide stability while solving local voltage constraint problems.

3. COMMUNICATIONS MODELS FOR EMERGING POWER SYSTEMS

Information and communication technologies (ICT) applied to supporting distributed power system elements in emerging power system networked instantiations, is at the core of the vision of a fully operational smart grid. Various papers have already addressed the key communication infrastructure requirements needed for ensuring enhanced performance, flexible and adaptable operations, reliable and secure delivery and business/economic aspects of future smart grid deployments. There have been several surveys of outstanding research issues [88]-[95].

3.1.1 Co- simulation: power/ communications networks

The underlying differences in dynamics characteristic of power systems and communications networks has led to an area of research that attempts considering both dynamics under the same framework. While the power systems are modelled using continuous time models, the communication systems inherit the implicit discrete event dynamics of, for example, a packed based communication. Hence, for off-line and/or real time co-simulation frameworks, the explicit accounting of the time scale dynamics of the application under assessment, is key in their validation.

Currently available co-simulation frameworks for joint analysis of smart grid power and communication systems have been reviewed [96] and that review notes that the research community has also begun exploring the possibility of using real-time simulation for co-simulation. Co-simulation environment for “hardware in the loop” or “software in the loop” validation of distributed controls have also been proposed [97].

Mets et al. provide an overview of various tools that would apply in smart grid research and in particular combined power and communication systems co-simulators [98]. The underlying research questions and design challenges are also highlighted.

The following smart grid simulation paradigms are mentioned: "i) combined simulation of power and communications systems, ii) Continuous time and discrete event simulation models, and iii) Emulation, Real-Time Simulation and Hardware-in-the- Loop Simulation". The paper highlights two major types of studies: "i) wide-area monitoring, protection and control, and ii) demand-response." At a more generic level, and as expected, two broad lines of research have been identified: one that focuses on specific smart grid use cases, and another that can be used for a wide range of use cases. There is a growing body of work in the area [99]-[101].

3.1.2 Networked control, Information management and planning

Research scope on the impact of delay/latency and time constraint applications on smart grids is wide. Here a selection of recent findings is presented. Scaglione et al., discuss the evolution of the power grid cyber-physical system and its increasing reliance on communications efficiency as generation capacity continues to grow [102]. Underlying power grid control mechanisms are presented, and the difficulties of developing and deploying networked control solutions are discussed. The concept of co-design is suggested as an analogy to cross-layer communication systems design.

In a related paper, Liang et al., give a comprehensive literature survey on the stochastic information management schemes for the smart grid, where models of individual components are jointly included in a system-level stochastic information management framework [103]. It is rightly suggested that a joint system planning approach will facilitate the planning and operation of future smart grid deployments. And these planning approaches will become by nature multidisciplinary. Planning of smart grid communications networks are also addressed in various other papers [104] [105].

St Leger et al. developed a unified quantitative methodology for modelling both the cyber and physical components of the smart grid as well as their interdependencies [106]. Xu et al., investigated wireless network delay performance in the smart grid environments to support time critical applications [107]. The theoretical upper and lower delay bounds in wireless (access and backbone) networks are investigated. Packet loss and latency on real-time demand response have also been addressed [108]. Communications latency has also been modelled in order to study the restoration time of a multi agent system approach, in response to abnormal events in a smart grid environment [109].

3.1.3 Reliability aspects and Cyber security

There are two aspects of a power system that can affect in a similar way the quality of service of delivery: in terms of the cyber security of the system, investigation and solutions are mainly focusing on the ICT technology related elements of the grid. In contrast, the reliability aspects of power systems can be affected by the ICT elements of the smart grid, and also can be affected by the underlying power system design and power systems interconnections, and their inherit or natural characteristics.

A set of recently published papers have addressed cyber security challenges, analysis and research related to smart grid environments [110]-[116] and reliability models and evaluation of smart power systems [117]-[119].

3.1.4 Communication infrastructure evolution/networked control

It is well known that current communication infrastructure has the following limitations [88]: fragmented architecture; examples of lack of adequate bandwidth for two-way communications; lack of interoperability between system components, and it will not be possible to handle increasing amount of data.

The most difficult type of problems in networked control applications are evident when the time scales of control and communications become non separable. An intrinsic theoretical challenge is hence inherit, and establishing an optimal control and communication strategy becomes an underlying research issue. In a networked environment, the resilience/reliability of future micro-grids will highly depend in their capacity to operate in agreement with neighbouring micro-grids.

However, neighbouring micro-grids should be able to continue to operate under suboptimal communication scenarios, for example, by falling gracefully back to a local mode of operations. The modelling and analysis of physical and communication system operating under faulty conditions will be the focus of high interest for designers and operators.

Together with the technological advances and novel ICT solutions, innovation in power devices technologies with enhanced local capabilities as well as embedded communications and information exchanges features, spanning from network devices to domestic appliances.

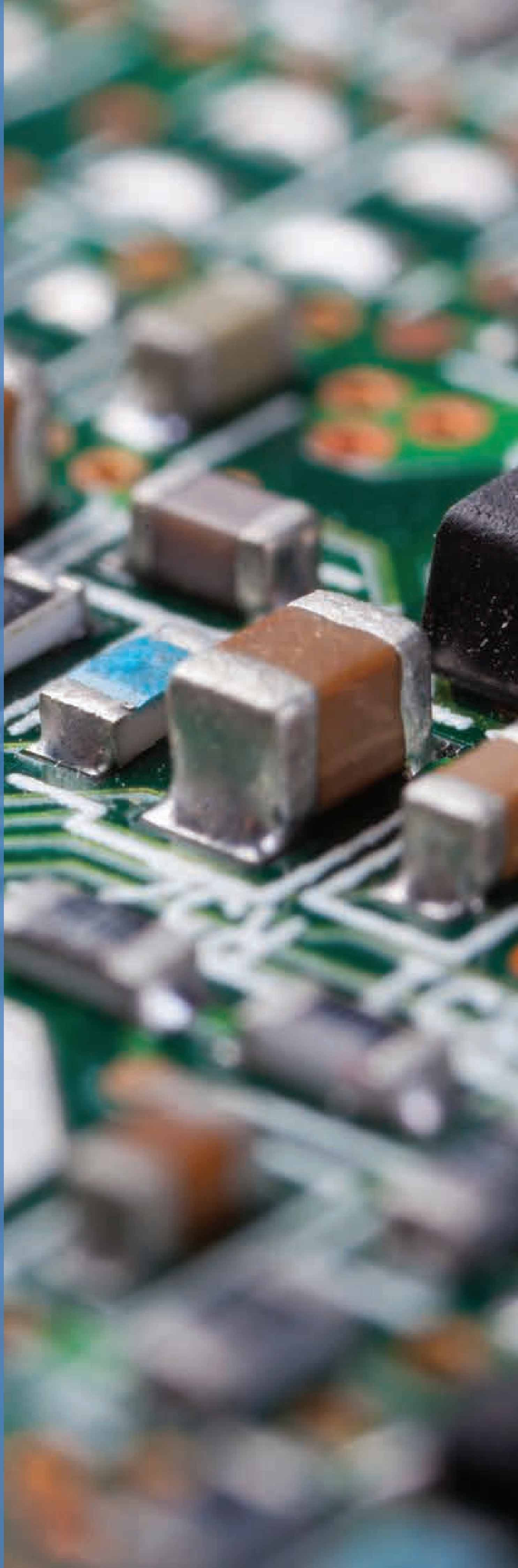
These novel appliances and network devices will impose different requirements on communications technologies and associated applications. This will become more relevant as and when generation capacity reaches high penetration closer to demand points.

3.1.5 Monitoring and sate estimation

As sensor technology continues to develop and to be deployed, measurement based operations and maintenance of smart grid will require large amounts of data to be processed. Hence co-design/co-simulation of smart grid systems that will not only consider the communication infrastructure in isolation or loosely coupled, but a system where communications and information data are more integrated and coexists with pre-processed information, will be an increasing subject of investigation. How to solve aspects of data privacy and security, its impact on communication requirements and the reliability of the network will continue to be topics of research interest. For example, ICT supporting infrastructure to advance metering / state estimation techniques at the level of the distribution network requires further investigation, and should also focus on developing adaptable supporting ICT infrastructure. Also, the monitoring and control schemes currently deployed at the distribution level, might not scale well when emergent new smart grid applications are being deployed. Furthermore, as mentioned before, operating the smart grid with only partial information of the rest of the interconnected grids devices and applications may become a common day to day operations regime. In this context, the search for alternative and/or readily available ICT technology and standards, like e.g. broadband PLC, could be further exploited as a backup to other means of communication.

3.1.6 Co-design and co-simulation

Another area of increasing importance is on future joint-planning / co-design / co-simulation of micro-grids where the communication infrastructure needs to be considered as an integral part of the application under consideration rather than a loosely coupled supporting feature of the physical network. For example, innovative real-time energy dispatching application that considers using electrical vehicles as an active smart grid element, and at the same time being aware of the stochastic nature of available renewable sources, will need at its core, a suitable ICT infrastructure, that will require an application specific co-design/co-simulation research effort.



4. CONCLUSIONS AND RECOMMENDATIONS

Power electronic equipment presently exists in electricity networks and is modelled adequately for today's needs but that is because some of its interactions and properties can be ignored while its penetration in the network is small. An example is the modelling of the fault current contribution of an inverter which is small in comparison with a conventional generator and can presently be ignored but when a network region becomes dominated by inverters there will be a need to model fault responses in detail to redesign protection grading.

Power electronic devices are fundamentally different from electromagnetic machines in a number of ways, principally in that circuit quantities can change much more quickly, the steady-state and transient properties are governed by control actions not physical component values and the devices need to self-protect against over-current rather than offer a useful emergency short-term rating.

A further important difference, in part following from the crucial role played by the internal control mechanism, is that nominally similar equipment from different vendors may have significantly different responses to disturbances arising from different choices made in the control system. This makes generic modelling and aggregate modelling difficult. Further, there are not yet accepted classes of controller such as those that exist for the excitors and governors of synchronous machines. There is a need, through international bodies perhaps, to press for development of a range of classifications and agreed standard models for various types of power electronic equipment (as is now happening in the specific example of voltage-source HVDC).

In general, time-domain models based on a full physical representation of the technology emerge quickly but are not suitable for inclusion in system-wide studies because of the large computational effort required to simulate all components to that level of detail. For such studies there needs to be a set of verified and agreed reduced models that capture the dynamics across the timeframes of interest. Reducing model order to achieve accelerated simulations times needs to be done in a systematic fashion and confidence built through open verification. The need for reduced models is met to some extent by "black-box" models (ones in which the internal workings are obscured) released by equipment vendors for particular software platforms. However, such models are only known to be valid for one implementation of a device and are not open to being adapted to variants of the device and not verified for unusual working conditions. Only later do generic, open and modifiable models emerge. Because technology in power systems applications of power electronics is still advancing on many fronts, it will some time to come before the models mature.

Time-domain modelling is a starting point only. Stability assessment via time domain simulation is not a sensible approach – frequency domain models needed that have been formed by linearising the device models around an operating point. Automated means to do this are present in most commercial packages and handle linearization of well-established network equipment but emerging technologies present fresh challenges in linearization that need to be tackled.

Another specialised form of modelling for which models are slow to emerge is the modelling of the fault current contribution. Again, the fault response is subject to large differences because of vendor specific design choices and is difficult to validate. The modelling of power converters under fault conditions is immature in general and only really undertaken for wind turbine interfaces and HVDC converter stations.

Perhaps the biggest challenge facing modelling of a future power system is how to model across the discrete-time/continuous-time divide, how to include event-driven systems such as communication networks and how to capture the salient properties of systems that happen on a wide variety of time frames. We are really facing a need to model systems-of-systems in which some of the systems call for very different modelling approaches to others.

A key development will be the means to couple models developed in different modelling environments and be able to simulate large complex systems-of-systems in reasonable computation time. There are surely lessons to be learned from mixed-physics, mixed-timescale modelling undertaken in other engineering fields and in biological systems.

4.1 Power Electronics By Technology Area

4.1.1 Wind

Considerable effort has been put into modelling the power electronic elements of wind farms and in general the models cover the foreseen needs or will do soon.

4.1.2 DER

Modelling at individual technology level is in hand if not complete for time-domain studies. Stability and fault-flow models are immature. Modelling for micro-grids is probably running ahead of modelling for gird-connected cases (because of the high penetration power electronics in micro-grids and the strong academic interest) but many of the principles now established in micro-grids will transfer to the grid-connected case when the need is there.

For system-wide studies, there will be a need to form aggregate models and verify them for how a collection of DER respond to grid disturbances (of frequency or voltage magnitude or fault conditions) and how they respond to requests for systems services (reactive power or real power modulation) and what payback might be incurred. It is important to recognise that some DER will be single-phase connected and will be controlled and will respond differently to three-phase devices.

4.1.3 HVDC

There is a strong concerted effort through Cigré to categorise models and expose the different capabilities to scrutiny. It appears that the sector has responded well to a perceived need and that sufficient effort is being directed to make good the modelling gaps. There will be remaining issues to overcome in providing open models where control format and tuning parameters are proprietary.

4.1.4 FACTS

FACTS devices have been in the literature for a long time and the reactive compensation devices relatively common in practice. This should be a mature area but there are still inadequacies in the way the devices and their controls are represented. This is particularly so when considering modelling support and tools for tuning multiple controllers and in representing co-ordinated control.

4.1.5 D-FACTS

Distribution system use of power electronics is immature in comparison to transmission use and so the models are immature also. In addition to carrying over the modelling tools from transmission application, the placement in distribution results in an emphasis on operation in unbalanced networks (including re-balancing as network control service) and harmonics studies (including compensation and/or damping of harmonics). Models to represent these properties in standard power systems studies will need to be developed from scratch.

4.1.6 Loads

The use of power electronics in power conditioning in loads across the domestic, commercial and industrial sectors is widespread. Direct-on-line connected heaters, motors and lighting are a diminishing fraction of the total load. Composite load models need to keep abreast of this and properly represent the static and dynamic characteristics of loads interfaced through power electronics particularly in regard of constant power loads. Further, load-side power electronics can contribute harmonic currents, either directly or in response to harmonic voltage excitation. It is important to recognise that as switching frequencies inside equipment rise, it is emissions in the 10 – 100 kHz band that may be more prominent than traditional low-order harmonics and modelling of distortion propagation and aggregation in this frequency band is not common and little data exists on which to base models.

4.2 Communications Technology

The ICT technologies features required by new smart grid applications and services, not only depend on the particular application, but will also differ from country to country (e.g. different distribution network topologies in the U.S. as in the U.K.), and among energy provider companies within a country or region.

The investigation of interdependencies among application components (ICT, power devices and smart grid applications) is needed, and the associated performance evaluations will most certainly be application dependent. For example, a novel real-time energy dispatching application, that considers using electrical vehicles as an active smart grid element, and at the same time being aware of the stochastic nature of available renewable sources, will require at its core, a suitable ICT communication infrastructure. The development of applications such as this, will immensely benefit from an application specific co-design/co-simulation based research effort, which in its most ambitious instantiation, should consider all phases of the life cycle of the smart grid service/application, as well as maintenance and operational aspect of the application.

What is needed is a joint multidisciplinary research effort to identify a purpose and focus to future development on co-design/co-simulation and modelling tools. A coordinated effort by researchers, developers engineers and operations personnel is needed to address all aspect of the life cycle of the new smart grid applications/services including operations and maintenance aspects.

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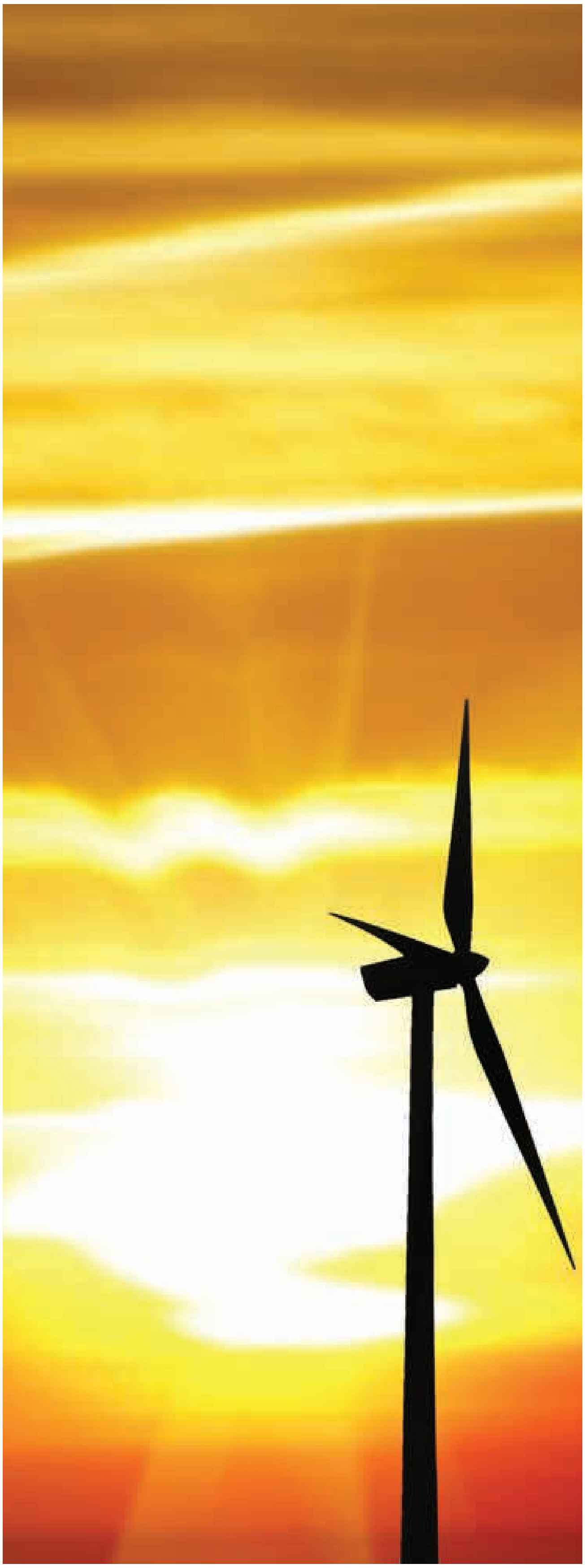

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