Electricity Grid Stability
with many small-scale renewable energy inputs

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The Problem:

The electricity companies cap the input of electrical energy into the grid from many renewable sources in order to ensure grid stability. For instance, Scotland is well provided with renewable energy, and has many wind farms, but 75% of the possible generation is unused because the energy companies limit the amount that they can put into the grid to ensure grid stability.

Grid stability problems cause fluctuations in frequency and voltage; these can sometimes result in resonance – the entire network rings like a bell – and can cause major outages of generating capacity. Until now, stability was maintained by having large mechanical moments of inertia in the system through steam turbine driven alternators with large values of rotating mass. These iron out short-term fluctuations between supply and demand. You can obtain a feel for the source of the problem if you have an old AM radio tuned to the long wave between stations and listen to it close to any pylon-supported electricity cable. You will hear chaotic random noise caused by the many changes in demand, both small and large, that are continuously happening across the network.

The problem is exacerbated because every large alternator has its frequency set by a very simple control system called a "Watt Governor". These all have very similar characteristics, and it is possible to have a destructive resonance, (harmonic instability), occurring where two or more Watt governors' outputs are oscillating in antiphase in different parts of the grid network. It is very difficult to trace the source of the problem and recovery can be very difficult to achieve.

There is a further issue in that some electrical loads have a lagging power factor, the current drawn by the load lags behind the voltage, (many types of electric motor do this), and other loads, (switch-mode power supplies, for instance), have a leading power factor. The supply characteristics need to match the load characteristics or the voltage wave-form is distorted which causes problems for some generators and for many types of load.

The energy companies cap the supply from each renewable source in such a way that the large rotating masses of the gigawatt generators dominate the network. This, in effect, throws away a large proportion of the available renewable energy whilst continuing to supply the same quantity of energy via large steam turbines driven by fossil fuels, (including nuclear fuels). Scotland, for instance, is blessed with substantial renewable energy sources, but typically, about 75% of this is discarded in the interests of grid stability whilst a similar amount is generated from fossil fuel power stations.

There are proposals for solving this problem by providing undersea DC links between Scotland and England. This is enormously expensive, (I have heard £250bn quoted for just one of the proposed systems), and uses a single core cable with the sea as the return path for the current. It is well known that passing a current of about one amp per square metre through water for a few seconds will temporarily stun all of the fish. This is used for population and species diversity studies and also for poaching. I wonder what the effect on sea-life is of having several million amps sent out from an electrode of only a few tens of square metres. Any scientist wanting to work in such waters to study this should take serious precautions against electrocution.

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The proposed solution:

This document proposes a different stratagem for control of the whole grid that will ensure that supply and demand always match, that will ensure a stable and accurate frequency and voltage at all times, that the power factor and phase imbalance issues are matched between demand and generation and will enable rapid recovery from major faults or disruptions.

1. The first requirement is to communicate a stable timing signal, the master timing signal, to every generator, whether it is a multi-gigawatt alternator set in a power station or the static inverter connected to the solar panels on your own roof. The easiest way to do this is to derive it from the time signal received by many clocks and watches from terrestrial transmitters in many countries or by the GPS systems from satellites that cover the globe. This means that every static inverter and alternator control system on the network will need an upgrade or replacement to enable the use of these communications from the control centre.

   The static inverters associated with domestic or industrial solar panels will need either an upgrade or a replacement with one that provides this means of control. It is estimated that the additional circuit required for each inverter would cost around £20 to manufacture. A simple signal would indicate to the inverter the amount by which it must lead or lag the current grid wave-form.

   Wind turbines all use induction motors and thus run at constant speed regardless of the wind speed. This causes them to generate power with a leading power factor that varies with the wind speed and thus the amount of power that each is generating. In the long term, it may be more flexible to replace the self-energising induction rotors with permanent magnet induction motors or with controlled rotor or stator energisation. This will generate power at a variable frequency that can then be rectified and then inverted in a controlled way to match the needs of grid stability. In the short term, the alternative is to adjust the pitch of the turbine blades to give the required leading or lagging power factor, which, in turn, depends on the signal from the control centre.

2. The second requirement is to limit the power put into the grid when there is a surplus of generation. This needs to be done on an area-by-area basis to minimise transmission losses. For the larger generating systems, an independent communications network should be used, but it may be that the telephone, mobile phone or Internet systems are adequately secure to carry the signals to the many thousands of smaller renewable sources. Here there are three stages of limitation:

   - The first stage will only apply to those generating systems that use fossil fuel or nuclear energy to generate steam for turbine-powered alternators. They need to run at a steady rate to be efficient and their production rates should change only very slowly. Their outputs should always be minimised to make best use of the available renewable resources.

   - The second stage applies to those renewable systems that can store power, whether it is a large pump storage scheme such as Cruachan, a battery farm or a battery attached to your rooftop solar panels. Surplus power is diverted to storage when there is a surplus, and the stores are drawn on during every short-term deficit. Such systems need to have a two-way communication with the control centre so that the accessible stored energy, available storage capacity, generation rate and rate of energy diverted to storage are always known. The regional or national control centres will then be able to optimise their use.

- The final stage is when the systems with storage are not exporting any power at all, everything being generated is going to storage unless the storage is full, and a reduction of supply is still needed so that renewable sources with no storage have to be restricted. With a properly balanced grid, this last stage should only be called upon very rarely.

3. The third requirement is to balance the three phases. Here the system needs to know the relative load on each phase and to match this by adjusting those small generators that feed power into only one phase, (probably all are renewables), so that the current going into each phase matches the different loads on each phase in that area. Long-term imbalances between the loads on the three phases requires that some significant single-phase loads be transferred to a different phase. There are already systems in place to do this.
4. The final requirement is to match generation with the local power factor, and here the system should generate a signal for each area that determines the amount by which each generating system should lead or lag the local grid waveform. The static inverters on renewable energy sources are tied to the local grid frequency but with a bias that causes it to lead or lag the grid waveform by an amount that will match the local power factor. An adjustment of this bias applied across the whole grid network will also continuously remove any slight deviation between the grid frequency and that defined by the master timing signal.

For the purpose of control of these signals, it is necessary to take measurements at critical points around the electricity grid network. The obvious points to consider include:

- both sides of every transformer on the system;
- both sides of every circuit breaker on the system;
- major generation inputs;
- the draw off points of the most significant loads;
- consider providing such measurements on other parts of the grid that have a higher risk of disruptions, as this will facilitate recovery from faults.

The measurements required are of:

- voltage phase to phase,
- current in each phase,
- power factors on each phase,
- and phase differences between different measurement points across the whole network.

Please see the appendix for details of the measurement techniques required.

A computer containing a dynamic model of the grid is used to compute what changes are needed to balance supply and demand both locally and nationally, to maintain balance between phases and to manage the power factor at each measurement point. Some research and development work is required to produce a model that will perform the necessary diagnostic and recovery decisions sufficiently quickly and to enable the physical grid network configuration changes to be updated and included as they occur.

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Achieving this may require many currently manually operated switches to be automated and controlled remotely from the model; optimal control of the grid for recovery from major disruptions may also require the provision of alternative routes for power that are normally unused. A further operational requirement is to update the model immediately any installation or configuration changes are put into service; a model that fails to match the current state of the grid would be useless when a significant fault occurs.

Clearly, to perform this control across the whole network, it is necessary to have a single control centre for the whole grid managing the master timing signal and the bias to the power factor that maintains the overall frequency and voltage stability. The other issues are more local in their demands and effects and regional control centres may manage these functions. This local control will also manage the quantities of power imported from or exported to neighbouring regions.

These changes are communicated in two ways.

- Firstly to the large and slow to respond power stations so that their use is minimised relative to the more responsive renewable sources, to ensure that there is capacity in the renewables to take up the slack in any sudden load change.
- Secondly, to manage the contributions from those renewables with storage quickly enough to maintain grid stability at all times.

The effect of this system will be to achieve a dynamically stable grid that can respond rapidly, (within one or two cycles), to unexpected major events including lightning strikes, major storm damage and hostile events such as vandalism, sabotage and war that disrupt the grid.

It should be clear from the above that, in the event of multiple faults that divide the grid into two or more disconnected sections, this system will maintain synchronisation between the different sections whilst the faults are repaired. This allows the disconnected sections to be reconnected without difficulty; with the present grid control; this is extremely difficult and very few engineers have the necessary skill.

Rapid and automatic response to major disruptions will require automation of many switches that are currently manually operated. It may also be a requirement to provide additional alternative network connection pathways to minimise the scale of the disruption after a major upset.

For phase balancing, it is possible that some renewable sources could automatically provide different power levels to the different phases.

Appendix:

The measurement of phase differences
between different parts of an electricity grid network.

It is necessary to have a common absolute timing reference to compare the phase differences across a grid network covering a large area. This could be the time signal generated by a terrestrial transmitter, a signal communicated through a wire or optical fibre network or a signal derived from the global positioning satellite system. The receiving system at each measurement point should establish a reference timing point for each cycle: on a 50Hz system, this will be every 20ms, for a 60Hz system this will be every 16.6667ms. This should be expressed as an integer number starting from a predefined precise integer hour, minute and second. Adjustment must be made for the signal delay from sender to receiver. For terrestrial radio signals or a wired or optical fibre network, this will be a fixed value that can be set up at the time of installation. For the satellite signal, because the satellites move, the satellite location contained in the transmitted data is used continually to calculate the timing signal. Because there are many GPS satellites, and each moves around the globe, the data from all those within range are averaged to achieve a reliable and accurate timing signal; the technology for doing this is well established and is used in every satnav system.

A measurement of voltage and current in each phase taken every 20µs will give a resolution of 1:1000 (for 50Hz; 1:833.33 for 60Hz), for these measurements. The time differences between the reference signal to the zero crossover and peak in each direction of current and voltage on each phase are communicated to the control centre through a dedicated communication network. This communication network should be independent of the Internet for reasons of security: the potential for hostile disruption via the Internet of a critical strategic infrastructure, (see reference), is clearly unacceptable. At the control centre, these timing signals, with the corresponding magnitude data, will give voltage, current, power factor, true frequency, phase to phase balance, as well as the phase differences between different measurement points.

With this information, faults on the grid network can be quickly identified and their location and characteristics analysed to enable speedy stabilisation of the grid whilst minimising disruption. By analysing the shape of the whole waveform at each measurement point, it would also be possible to identify abnormal loads or power sources on the grid having faults that cause unacceptable shape factors, and in some cases send signals to oblige these to disconnect until the fault is resolved.

Reference:

The Management of Critical Strategic Infrastructure: John McCulloch. This document is available on **http://www.intint.co.uk/environ.html**