UNIVERSAL APPLICATION OF SYNCHRONOUS ISLANDED OPERATION

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ABSTRACT

Synchronous islanded operation keeps an islanded system in synchronism with the main power system while not being electrically connected. The challenges associated with the multiple-set application are considered in this paper.

INTRODUCTION

Power system islanding is receiving an ever increasing interest as a method to improve distribution system security and protect the economy against the consequences of blackout. Islanding poses several operational challenges, not least, the danger of out-of-synchronism re-closure of the island onto the main system. 'Synchronous islanded operation' has been proposed as a means to keep the island in synchronism with the main system while not being electrically connected.

A reference signal containing phase and frequency information is transmitted from a secure part of the network to the distributed generator for use as a control signal. The objective is to obtain a control response to a load disturbance that is similar to fig. 1. The phase difference should remain within acceptable levels and return to near zero in steady-state.

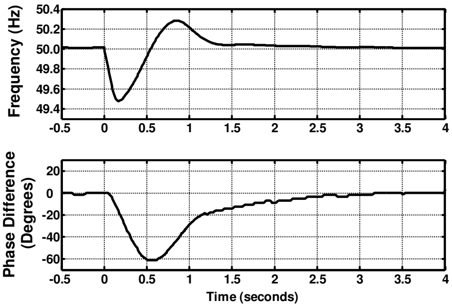


Fig. 1 Synchronous island response to a load acceptance

Previous work by the authors has applied an appropriate control algorithm, for single-set operation, to a diesel generator [1], and shown that synchronisation angles of up to 60° should be acceptable for this type of distributed generator [2]. Thus, it was demonstrated that such control is feasible.

In the diesel generator experiment [1], the reference was transmitted as an analogue signal at radio frequency, but it may prove difficult to calibrate such a system for large scale implementations. Thus, time-stamped phasor measurements are being investigated as a universal solution, allowing the reference signal to be transmitted across shared internet protocol communications, which are both readily available and cost effective. A single-set laboratory demonstration by the authors has illustrated the benefit of Global Positioning System (GPS) time-stamped phasor measurements in this application [3]. While improving accuracy and removing the problem of time error, i.e. the correct alignment of the phasors in the time domain, potential problems can still arise from communications time-delay and information loss. It is also important to consider the adaptations required to accommodate multiple-set synchronous islanded operation. Extrapolation of the reference signal to mitigate effects of reference signal time-delay, island detection and control initiation, load sharing, and multiple-set isochronous frequency and phase difference control, are discussed in this paper.

PHASOR MEASUREMENT UNITS

Phase difference can be calculated using two phasor measurement units (PMU), one installed at the main distribution sub-station or at a secure point on the meshed transmission system, and a local PMU at the distributed generator. PMU operation is discussed in [4].

Removal of Alignment Delay

Time-delays in a control system tend to reduce its stability. In the single-set scenario of synchronous islanded operation, it is the time-delay introduced during the process of transmitting the reference signal information that will cause most difficulty. The extent of this delay depends upon the communications method employed. Although this delay is external to the control loop, by aligning the time-stamped phasor measurements an equal time-delay is added to the feedback part of the control loop. This removes the steady-state error that would exist if the two measurements were not aligned up correctly in the time domain, but in doing so reduces stability [5].

To remove the alignment delay, a simple predictive method can be introduced that extrapolates beyond the most recent measurement. Fortunately the reference signal is a sinusoidal waveform and thus is relatively simple to predict, at least in the short term.

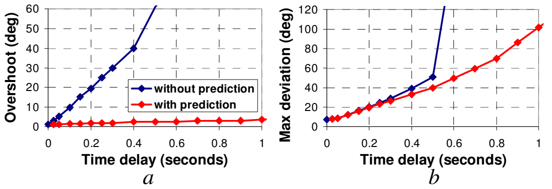
By taking the time domain representation of a phasor, equation (1), it can be seen that to calculate the phasor angle at a point in the future, three variables must be known. These are the initial angle θ, the frequency f, and the time difference t_d, between the most recently received phasor measurement time stamp, from the reference PMU, and the latest local PMU time stamp. Note that V_m is the voltage magnitude and $v_{(t)}$ is the time varying voltage.

$$v_{(t)} = V_m \sin\left(2\pi f t_d + \theta\right) \qquad (1)$$

These terms are known to a high level of accuracy. For a 50 Hz system, if GPS or similar method of time-stamping is employed, it is possible to achieve resolutions of time, phase angle and frequency of 1 µs, 0.018° and 0.0025 Hz respectively. This scheme will be able to cope with even a highly variable time-delay, because t_d is re-calculated after each phasor measurement update. Thus it should be possible to predict the phasor at a point in the future with a high level of confidence. An assumption must be made that the frequency of the reference waveform remains constant during the time period in question. This is a reasonable assumption because the frequency of the main system is normally very stable. However, during a system event an error will be introduced.

Performance of Predictive Method

Fig. 2*a* compares simulated system performance following a disturbance in the island at different fixed time-delays, both with and without reference signal prediction. The measure of degradation is the phase difference overshoot. The predictive method by extrapolation shows a dramatic improvement, and this would be the case even if the delay was variable, or in the presence of information loss.



a *b*

Fig. 2 Effect of a) island event and b) reference system event on control

If a disturbance occurs on the reference system, the predictive method does not provide the same improvement as in the previous example, shown in fig. 2*b*. This is because the reference system frequency is assumed to remain stable in steady-state. Despite this, the predictive method improves the stability of the system. The measure of degradation applied is the peak phase difference reached during the event.

MULTIPE-SET SYNCHRONOUS ISLAND

As there may be considerable distance between distributed generators, a suitable supervisory control system is proposed that could operate using internet protocol communications and slow information update rates.

Simulation Model

A simulation model of a low voltage, 400 V, radial distribution network is constructed in Mathworks SimPowerSystems, as shown in fig. 3. The model is adapted from a previous study [6], and the parameters used are available in [7]. The network contains three distributed generators capable of synchronous island control.

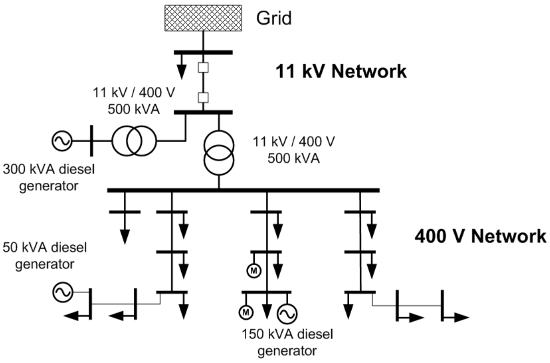


Fig. 3 Simulation model

Island Detection and Island Control Initiation

In the simulation, islanding detection is achieved using angular difference [8], although any suitable loss-of-mains method could be employed. Islanding detection and control initiation are performed independently by each distributed generator; each assuming single-set operation until the supervisory controller can react.

Fig. 4 shows the formation of an island with a large difference in load and generator output. Following islanding detection, the distributed generator control mode is changed, and several seconds are needed to establish stable synchronous island control and reduce the phase difference to within an acceptable margin.

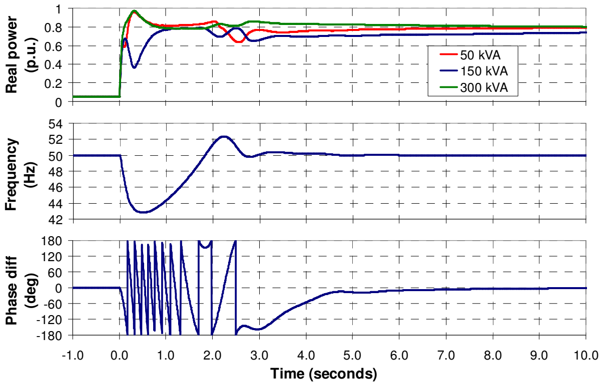


Fig. 4 Island initiation transient for large load-generation imbalance

It is important that automatic re-closing relays do not operate during the stabilisation period. Thus, it is proposed that at least 10 seconds delay should be allowed for the purposes of synchronous islanded operation. Some utilities currently use automatic re-closing delays of this magnitude. Consequently, it is the load disturbances and phase deviations that occur during normal island operation that will have greatest bearing on the schemes suitability.

Load Sharing

Once the island has stabilised, synchronous islanded operation must be held indefinitely. Thus a controller is required which can deliver secondary control functions such as load sharing. Conventional practice would suggest the use of a power-frequency droop characteristic [9]. However, real power load sharing in this manner is not suitable for synchronous islanded operation, because the frequency must be tightly controlled. Thus, the application of communications to load sharing will be explored.

From a system stability perspective, the load-frequency control set-point should not be updated too frequently, typically 2 – 4 seconds [10]. This allows sufficient time to acquire data from the system, make a decision and send the information back to the generators, possibly using shared internet protocol communications.

An additional difficulty for synchronous islanded operation is that changing the generators' real power set-points can introduce a frequency disturbance and thus increase phase deviation. The problem can be relieved by introducing a rate-limit for any real power set-point adjustments. When the generator is controlled by a proportional, derivative (PD) phase difference controller and proportional, integral, derivative (PID) governor [1, 7], a ramp of power output will introduce a steady-state phase difference error during the time of ramping. Thus a balance must be achieved between the desired rate-of-change of power and the acceptable steady-state phase difference error. The controller that shares the real power load among the generators in the simulation is shown in fig. 5.

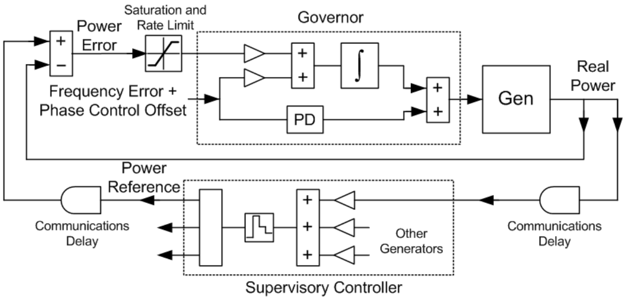


Fig. 5 Load sharing controller for phase difference control

The simulated example in fig. 6 shows the load sharing after islanding with a close match of load and generation output, but with a large difference between individual generator power outputs. By endeavouring to restrict the phase difference steady-state error caused by ramping power, the load sharing process has been slowed considerably.

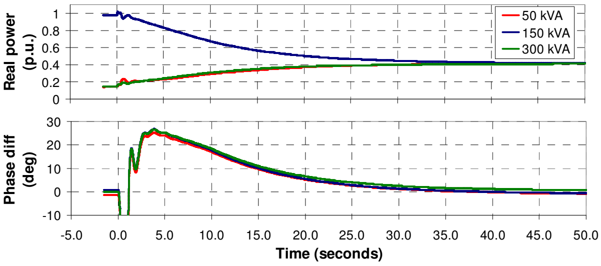


Fig. 6 Load sharing during phase difference control

While it is acceptable to share voltage and reactive power by using droop, a similar communications based scheme would also be possible.

Multiple-Set Phase Difference Control

In a multiple-set island, using a single set to control phase difference is easier to implement than a multiple-set control option. However, the latter has some advantages: all generators respond to control phase difference, and following the loss of a generator there will be a rapid return to synchronous islanded operation.

In schemes with many distributed generators performing primary PID control functions, measurement errors can cause the control systems of each generator to conflict. The solution is an accurate measurement of variables combined with communications between sets. Typically this is available for distributed generators in close proximity to one another, i.e. in the same building [9]. A similar scheme could be applied using modern communications methods, such as that shown in fig. 5, which facilitates multiple-set phase difference control and load sharing.

The synchronous machine inertia from distributed generation not involved in phase difference control, while reducing frequency deviation, can increase the maximum phase difference. Multiple-set phase difference control counteracts this effect, as shown in fig. 7.

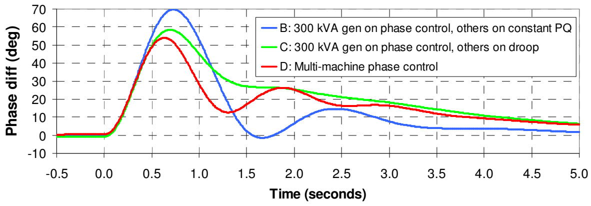


Fig. 7 Phase deviation following load rejection for different control options

An enhanced governor could be used to improve the response. For example, in the simulation a 6 % rated real power load disturbance can occur without 60° phase difference being exceeded. In experimental single-set tests by the authors [1, 7], a 10 % rated load disturbance was possible with a standard product variable gain governor, improving to 25 % when employing a governor with supplementary inputs.

Other Considerations

Protection and Power Quality

Protection co-ordination is complicated by the variable conditions of grid connected mode and formation of islands with different sizes and composition. Thus some form of adaptive protection scheme or communications based protection may be appropriate.

Power quality issues must be considered. These include voltage control and stability, harmonics, unbalanced loads and voltages, the control and stability of power and frequency, earthing, and recovery from faults.

Return-to-Mains Detection

Detecting the reconnection of the island to the mains when the two systems are constantly held in synchronism may prove difficult, as there will be little transient effect to observe. While this is not critical, a method for reliably detecting return-to-mains will be required so that generator control modes can be changed.

It is likely that the steady-state phase difference will vary more during islanded operation than when connected to the grid. Thus, return-to-mains detection could be based on the phase difference being close to the expected voltage phase shift estimated for that particular distributed generator and with a stability concurrent with grid connected mode.

Communications Outages and Security

With extrapolation of the reference signal in place, the control system can temporarily keep the island in synchronism during short communications outages, probably for one or two seconds. Longer communications outages will require shut-down of the island to prevent out-of-synchronism re-closure becoming a possibility. Built in redundancy for communications links, reference PMU, and the supervisory controller should be considered to minimise the chance of disruption. When using internet protocol communications for power system control, security of information and quality of service must be assured [11].

CONCLUSION

It has been demonstrated how the benefit of PMU can be extended for synchronous islanded operation by predicting the reference signal, thus removing alignment delay and improving controller performance.

The application of synchronous islanded operation to a multiple-set island has been considered. Several related operational and control issues have been discussed and investigated through a model of an islanded distribution power system, simulated using Mathworks SimPowerSystems. It was proposed that two-way communications with a supervisory controller be used to provide the secondary control functions necessary for stable multiple-set synchronous islanded operation.

Automatic re-close time delays should be sufficiently long to prevent out-of-synchronism re-closure during the settling time at island formation. However, the ability to constantly maintain synchronism is limited by the maximum load disturbance that may occur in the island.

Accurate load sharing was shown to be achievable during synchronous islanded operation when a supervisory controller is employed. A load sharing scheme was implemented that introduces minimal phase difference error during the load sharing process. The scheme can also eliminate the control conflicts that afflict multiple-set phase difference control. Multiple-set phase difference control is beneficial due to its fast response to disturbances and for the continuation of synchronous island control following the loss of a generator.

Other considerations requiring further work are protection, power quality, detection of return-to-mains, and communications outages and security.

The authors believe that synchronous islanded operation could form an integral part of future active distribution networks and, subsequent to this paper, plan to implement the abovementioned control functions in a practical demonstration.

ACKNOWLEDGEMENTS

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