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Management of a Multiple-Set Synchronous Island

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Abstract—The continuity of power supply can be improved by power system islanding. A possible solution, synchronous islanded operation, enables the islanded system to remain in phase with the main power system while not electrically connected, and so avoids out-of-synchronism re-closure. Specific consideration is required for the multiple-set scenario, and is the topic of this paper. A suitable island management system is proposed, with the emphasis being on maximum island flexibility by allowing passive islanding transitions to occur, facilitated by autonomous control. These transitions include: island detection, identification, fragmentation, merging and return-to-mains. It can be challenging to detect these transitions while maintaining synchronous islanded operation. A Mathworks SimPowerSystems simulation is used to investigate the performance of the island management system. However, return-to-mains is particularly difficult to detect, and so a method based on voltage phase angle variability is explored by using a laboratory demonstration and time stamped phasor measurements.

Index Terms—Distributed generation, islanding, phase control, phasor measurement, power distribution control, synchronization.

I. INTRODUCTION

THERE is potential to improve power system security by enabling sections of the distribution network to separate from the main power system and operate autonomously as power system islands. An increasing capacity of distributed generation connected at the distribution level [1], and the incorporation of technological advancement in digital control [2] and modern communications [3, 4] into power system operation, means that previously unworkable ideas can become a reality. Thus, as late, power system islanding has been receiving worldwide interest [5, 6].

However, for islanding to become widespread the major technological issues of power quality, protection, out-of-synchronism re-closure and earthing must be addressed [1]. The authors have concentrated their efforts on arguably the most serious of these issues, out-of-synchronism re-closure,

and have developed a control system to avoid its occurrence [7]. This concept is synchronous islanded operation, whereby the islanded system is held in synchronism with the main power system at all times while not being electrically connected. This is achieved by appropriate control and the transmission of a reference signal from the main power system.

Tests and simulation of a salient-pole alternator have indicated that in exceptional circumstances, such as power system islanding, synchronization angle limits can be relaxed in distributed generation of robust construction from those currently in use [8, 9], to about $\pm 60^\circ$. This gives the phase control system a realistic, although still stringent, target. A successful demonstration of single-set operation on a diesel generator has been performed [7], with the inclusion of time-stamped global positioning system (GPS) phasor measurements as a universal solution being considered [10]. However multiple-set operation is a more likely scenario and several additional challenges have been identified, which are complicated by the tight frequency control requirements of synchronous islanding [11]. The challenges include protection co-ordination, load sharing, suitable multiple-set frequency and phase difference control, and the effect of substantial renewable generation with variable power output on the control scheme. These issues are being considered in concurrent work. This paper addresses another concern; the design of a multiple-set island management scheme specifically for phase controlled, or synchronous, islands.

II. ISLANDING STATES AND TRANSITIONS

An island management scheme, in addition to providing stable steady-state control, must also be able to detect and cope with the various transitions and reconfigurations that may occur during islanding. These are as follows: island detection and identification, island fragmentation or distributed generator loss, return-to-mains detection, island merging, and island shut-down. These islanding state transitions are shown in Fig. 1.

The proposal is that not all island reconfigurations will occur ‘actively’ with prior-knowledge of the system operator, or will be executed by the utility’s control system. One example is the mal-operation of protection. Thus a suitable monitoring and control scheme is required which can act ‘passively’ as well as ‘actively’. The aim is, where possible, to use algorithms which operate locally at the distributed generator, for speed and reliability. However, a supervisory controller will

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Fig. 1. Islanding state transitions

provide a communications link between all distributed generators to ensure stability, continuous operation and correct performance of some operations. Such a structure encompassing local (primary) and supervisory (secondary) control loops is shown in Fig. 2.

The control system should be designed so that any telecommunications delays will have minimal effect, and that the system is robust to temporary communications outages. Further, it is envisaged that internet protocol (IP) communications will be used [10], as this would provide a low cost and feasible solution for the distribution network. Time-stamped phasor measurements [12] will play an important role in the operation of a multiple-set synchronous island.

Fig. 2. Local and supervisory control levels for multiple-set islanding

A. Island Identification

It is proposed that island detection be performed locally at each distributed generator for maximum speed of operation. On the detection of islanding, each distributed generator initially assumes it is in single-set operation and changes its control function accordingly. Island detection may be performed by voltage phase angle difference [13, 14], as the reference signal is available for phase difference control during synchronous islanded operation.

The scenario of single-set operation cannot be maintained indefinitely in the multiple-set case. So it is a requirement of the supervisory controller to identify which distributed generators are in each island, and initiate appropriate control, load sharing, etc.

It is proposed that voltage phase angle be used to identify distributed generation in the same island, or ‘island membership’, by comparing phasor measurements at the supervisory controller. Once the island is identified, steady-state control functions, such as load sharing, can begin.

B. Island Fragmentation and Distributed Generator Loss

The island may fragment into smaller islands, or a distributed generation may be lost from the island. Continued operation will require a reconfiguration of the control system. The supervisory controller must ensure that all distributed generators perform full frequency and phase control as required, and that load sharing between the separated distributed generators is suspended. The supervisory controller can detect island fragmentation by monitoring the voltage phase angle between each generator. A diagram for the island detection, identification and fragmentation functions is given in Fig. 3. Detection of return-to-mains or island merging is used to reset this function.

Fig. 3. Function for island detection, identification and fragmentation

The act of island fragmentation, or distributed generator loss, will cause a frequency transient and phase deviation. This represents a limit for synchronous islanded operation, the island can only successfully fragment if the load imbalance incurred is less than the maximum acceptable load disturbance.

C. Return-to-Mains and Island Merging

It is necessary to know when return-to-mains or island merging has occurred in order to change distributed generator control modes and ensure stable operation. However, it is

difficult to detect return-to-mains or island merging when each islanded power network is held in phase with the main system. This is because only minimal power system transient is observed. Since return-to-mains detection is not as critical as other functions, and can be performed on a timescale of several seconds, there are a number of possible solutions including; knowledge of all circuit breaker status, islanding detection techniques not based on frequency or phase deviation, power line carrier signals, power limits being reached, and power perturbations by the islanded distributed generation. A further method is proposed; based on the assumption that the grid connected phase difference is more stable than the islanded system phase difference. A measure of phase difference variance is taken over a specified time period, e.g. one second, and if the variance is below a certain threshold for 2 - 5 seconds, then return-to-mains is assumed to have occurred. The phase difference must be pre-filtered if noise and erroneous values are not to affect the operation of this function. A diagram of the process is shown in Fig. 4. The function is blocked for a period of time, 5 seconds, after island fragmentation or island detection to prevent control instability.

Fig. 4. Return-to-mains and island merging detection function

Island merging can be detected in a similar manner, by monitoring the variance of the voltage phase angle between the distributed generators, and would be performed by the supervisory controller.

III. SIMULATION OF ISLAND MANAGEMENT SCHEME

To illustrate how an island management scheme might be expected to operate, a model of a distribution system has been constructed in Mathworks SimPowerSystems, shown in Fig. 5. This 11 kV distribution network has three types of distributed generation: a 2 MVA diesel generator, a 4.51 MVA gas turbine, and a 2.5 MW fixed-speed wind farm consisting of several coherent induction machines. Only the diesel generator and gas turbine participate in the synchronous island control.

A. Control System

Distributed generator frequency and phase control is provided by a proportional, integral, derivative (PID) governor, with a fixed proportional gain phase difference controller. The system can operate with a multiple-set control strategy, i.e. multi-master control. However, this relies on a secondary frequency control loop facilitated by communications with a supervisory controller, which is also necessary for load sharing [11].

Fig. 5. Diagram of simulated network

Voltage is controlled by a load compensated, droop based scheme, since it is sufficient to maintain voltage within statutory limits during synchronous islanded operation. This could be upgraded in future implementations due to the presence of communications.

The distributed generator, control system, power line and transformer parameters are given in [15].

A suitable load sharing scheme and governor controller is selected for the different islanding states: grid connected, single-set island, master-slave and multi-master.

B. Island Management System

Island management for each distributed generator follows the flow chart in Fig. 6. Detection of islanding is performed locally, while island identification, fragmentation and merging detection are performed by the supervisory controller. Return-to-mains can be performed locally, but communication with the supervisory controller is preferable.

The presence of the wind farm is also identified, although it is not involved in the control of this system. However, some functionality is possible, such as blade pitch control [16], and may be called upon in further developments. Identification of all distributed generators and major rotating loads would allow system inertia to be estimated, and could form the basis for having adaptive governor gains in reconfigurable islands.

C. Simulation Results

The simulation shows how the island transfers through the different states. Islanding is initiated by the opening of circuit breaker 1 in Fig. 5. Fig. 7 shows frequency, phase difference and real power during the process of island formation, detection and identification. Satisfactory steady-state synchronous islanding control is achieved within 4 seconds, although equal load sharing takes longer to occur. The formation transient suggests a minimum setting for automatic re-closer delays of

at least 10 seconds [17]. Load sharing is performed slowly in this control system to reduce the associated phase error.

The generation to load imbalance at island formation is 1.5 MW. This occurs as a load rejection. However, there is a significant proportion of generating induction machines in the island, operating at a mechanical speed above synchronous. When synchronous machine speed increases rapidly following a large load rejection, the induction generators enter a different part of the torque-slip characteristic, and may even pass through zero torque, temporarily reducing their power output and resulting in a frequency decrease as seen in Fig. 7. Thus, large load rejections may prove less stable than large load acceptances in systems with large penetrations of induction generators.

Fragmentation and merging are initiated by the opening and closing of circuit breaker 2 in Fig. 5. Circuit breaker 1 closes, causing the island to return-to-mains. Fig. 8 shows the phase difference and real power during island fragmentation, merging and return-to-mains transitions. The load imbalance caused by island fragmentation is 160 kW, and it is possible to maintain phase difference within the $\pm 60^\circ$ limits. Following larger load imbalances caused by fragmentation or distributed generator loss, synchronous islanding can only continue if it can be assured that open circuit breakers will not close until stability is achieved.

Fig. 6. Flow chart for island management and controller selection

Fig. 7. Island formation, detection and identification

Fig. 8. Island fragmentation, merging and return-to-mains

Return-to-mains and merging detection using the voltage phase variance method works well in the presence of varying load. With constant load there is no phase variance, and the system may misidentify return-to-mains. In the simulation correct operation of these functions is only achieved by the periodic switching of a 4 kW load, i.e. a power perturbation. However, return-to-mains and merging detection may be easier to apply in practice due the presence of noise, measurement error, and variations in controller output and alternator speed. Thus, the next section explores voltage phase variance in a laboratory demonstration.

IV. VOLTAGE PHASE ANGLE VARIANCE – LABORATORY DEMONSTRATION

The voltage phase angle variance of an isolated machine, held in synchronism with the all-Ireland power system, is compared with that when it is paralleled to the power system.

Phase control is performed on a d.c.-motor driven alternator rated at 6 kW, using the control system described in [10]. The voltage phase angle is calculated every 100 ms by a GPS time-synchronized phasor measurement unit developed specifically for the task [10]. Data are aligned in the time domain using their time stamps, and where data from one location are missing or delayed, due to communications loss and latency, extrapolation of the phase angle from the latest measurement is performed [11].

When in synchronous islanded operation, a local mains reference is used and the alternator is held in steady-state, leading to minimum variation in phase angle. A sample of 40 seconds in this condition is shown by Fig. 9. For comparison, the machine is then grid connected. To increase voltage phase variation a remote reference signal is used, ≈ 120 km away [18], and the local load is varied. This is also shown in Fig. 9, and includes an offset added to account for delta-star transformer voltage phase shifts and average cross-system power flow related voltage phase shift between the two locations.

Fig. 9. Voltage phase angle during islanded and grid connected mode

The variance of voltage phase difference is calculated as follows. A moving average of 5 samples is taken, to reduce the effect of jitter and erroneous values. The variance is then calculated using 25 samples, or 2.5 seconds of data, using the sample variance equation (1). The results are plotted in Fig. 10, where variance is in the unit of degrees-squared. While the variance of grid connected mode is clearly less than islanded mode, maximum grid connected phase angle variance overlaps with minimum islanded phase angle variance. Thus it is suggested that several variance calculations occurring below the threshold be attained before return-to-mains is detected. In the simulation, three consecutive variances below a threshold were required. Thus, return-to-mains detection can take in the order of 10 seconds, which is acceptable as this is not as critical an operation as, for example, island detection.

$$\text{var} = \left(\frac{1}{n-1} \right) \left(\sum_{i=1}^n |x_i|^2 - \left| \sum_{i=1}^n x_i \right|^2 \right) \quad (1)$$

Fig. 10. Voltage phase angle variance during islanded and grid connected mode

Some islanding situations may require active methods, such as the power perturbations applied during the simulation to detect return-to-mains. However this laboratory demonstration indicates that phase angle variance calculation can be used to differentiate between return-to-mains and constant load states in rotating machines. The phase angle variance method of return-to-mains detection would be difficult in inverter only systems. Methods of island detection which do not rely upon frequency or phase angle changes could be used.

As the voltage phase difference samples are squared in (1), the accuracy can be of concern in the numerical calculation of variance if values are rounded and the variance to be measured is small. Thus a suitable algorithm must be chosen. Furthermore, removing erroneous values is important as they can significantly affect the calculation. Other methods of measuring variability may prove more suitable, such as mean deviation, or changing the sampling window.

Possible further work in this area is as follows: a laboratory demonstration of the multiple-set synchronous island control and management scheme, testing the ability of synchronous islands to be formed as a result of major faults, the application of more sophisticated control to improve responses to load disturbances, and the development of a suitable protection system for synchronous islanded operation.

V. CONCLUSION

An island management system suitable for synchronous islands has been proposed. By endeavoring to have undefined islanding locations, this system can reduce the chance of load being unnecessarily excluded from the island, and permits maximum flexibility to be attained by the islanded system.

However, the necessary detection of island transitions may not be straight forward in a system held in synchronism with the utility by appropriate control. Thus, suitable methods of detection have been introduced and illustrated by Mathworks SimPowerSystems simulation. These include detecting islanding and island fragmentation, and identifying the distributed generation in each island by monitoring the voltage phase angle difference between each pair of units, and between individual units and the utility.

Island merging and return-to-mains can be detected by monitoring the variation of voltage phase angle. However in simulation these transitions were difficult to detect without varying load in the islanded system. A laboratory demonstration with a d.c.-motor driven alternator has shown that this

technique can be implemented more easily in practice due to the presence of noise, etc.

The techniques discussed in this paper can form the basis of a laboratory demonstration for multiple-set synchronous islanding.

VI. REFERENCES

- [1] N. Jenkins, R. Allan, P. Crossley, D. Kirschen, G. Strbac, *Embedded generation*, IEE Power and Energy Series 31, London, UK: The Institution of Electrical Engineers, 2000
- [2] D. J. McGowan, D. J. Morrow, M. McArdle, "A digital PID speed controller for a diesel generating set", *IEEE Power Eng. Soc. Summer Meeting*, Toronto, Canada, vol. 3, pp. 1477 – 1482, Jul. 2003
- [3] M. Shahidehpour, Y. Wang, *Communication and control in electric power systems – applications of parallel and distributed processing*, Hoboken: John Wiley & Sons, Inc. – IEEE Press, 2003
- [4] T. S. Sidhu, E. Demeter, S. O. Faried, "Power system protection and control integration over ethernet-based communication channels", *Canadian Conf. Elect. and Comput. Eng.*, Niagara Falls, Canada, vol. 1, pp. 225 – 228, May 2004
- [5] N. Hatziaargyriou, H. Asano, R. Irvani, C. Marnay, "Microgrids: an overview of ongoing research, development and demonstration projects", *IEEE Power & Energy Mag.*, vol. 5, no. 4, pp. 78 – 94, Jul.-Aug. 2007
- [6] P. Lund, "The Danish cell project – part 1: background and general approach", *IEEE Power Eng. Soc. General Meeting*, Tampa Bay, USA, pp. 1 – 6, Jun. 2007
- [7] R. J. Best, D. J. Morrow, D. J. McGowan, P. A. Crossley, "Synchronous islanded operation of a diesel generator", *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 2170 – 2176, Nov. 2007
- [8] *IEEE standard for interconnecting distributed resources with electric power systems*, IEEE Std 1547-2003, Jul. 2003
- [9] Electricity Association: Engineering Technical Report (ETR) No. 113: Notes of guidance for the protection of embedded generating plant up to 5 MW for operation in parallel with public electricity suppliers' distribution system, UK, 1995
- [10] D. M. Lavery, D. J. Morrow, R. Best, P. A. Crossley, "Internet based phasor measurement system for phase control of synchronous islands", *IEEE Power Eng. Soc. General Meeting*, Pittsburgh, USA, pp. 1 – 6, Jul. 2008
- [11] R. Best, D. J. Morrow, D. Lavery, P. Crossley, "Universal application of synchronous islanded operation", *CIGRE seminar SmartGrids for Distribution*, pp. 1 – 4, Jun. 2008
- [12] *IEEE standard for synchrophasors for power systems*, IEEE Std C37.118-2005, Mar. 2006
- [13] X. Ding, P. A. Crossley, D. J. Morrow, "Islanding detection for distributed generation", *IEEE Int. Conf. on Power Tech.*, St. Petersburg, Russia, Jun. 2005
- [14] A. Ishibashi, M. Imai, K. Omata, S. Sato, T. Takagi, Y. Nakachi, S. Ogawa, "New type of islanding detection system for distributed generation based on voltage angle difference between utility network and distributed generation site", *8th IEE Int. Conf. Develop. Power Syst. Protection*, Amsterdam, Netherlands, vol. 2, pp. 542 – 545, Apr. 2004
- [15] R. J. Best, C. F. Ten, D. J. Morrow, P. A. Crossley, "Work package 3.3.1, construction of a transient simulation model that can change its topology from an interconnected network to an islanded network", *SuperGen V, AMPeS*, Sep. 2008
- [16] T. Senjyu, T. Kaneko, A. Yona, N. Urasaki, T. Funabashi, F. Yamada, S. Sugimoto, "Output power control for large wind power penetration in small power system", *IEEE Power Eng. Soc. General Meeting*, Tampa Bay, USA, pp. 1 – 7, Jun. 2007
- [17] *IEEE guide for automatic reclosing of line circuit breakers for ac distribution and transmission lines*, IEEE Std C37.104-2002, Sep. 2002
- [18] D. Lavery, D. J. Morrow, T. Littler, "Internet based loss-of-mains detection for distributed generation", in *Proc. 42nd Int. Universities Power Eng. Conf. (UPEC 2007)*, pp. 464 – 469, Sep. 2007

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