IMPROVEMENT OF TRANSIENT RESPONSES OF DISTRIBUTION NETWORK CELL WITH RENEWABLE GENERATION

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ABSTRACT

This paper assesses the transient operation and possible improvements of the voltage quality/stability of an 11kV distribution network-cell (DNC) with renewable energy sources (RES). The generators considered include synchronous generators (SG), doubly-fed induction generator (DFIG) and fixed-speed induction generator (FSIG) based wind plants and converter-connected generators (CCG) (e.g. photovoltaics, fuel cells, etc.). The generators are modelled in detail (considering voltage/current limits, aerodynamics, multi-mass models, etc.) in order to reflect appropriately their participation regarding system stability. Various DNC operating conditions, load type and compositions and a diverse range of generation scenarios are considered. Extensive results are presented and conclusions are drawn from a set of more than 500 case studies together with potential corrective actions to improve DNC stability.

DNC MODELLING

The test system used in the study is shown in Fig. 1. It is broadly based on a typical UK 11kV distribution network where a SG equivalent source (*External Grid*) with a symmetrical fault level of 500MVA feeds the network at 33kV. 11kV system is supplied by a 33/11.5kV, 12/24MVA, Dy11 transformer which has a 21% impedance with an X/R ratio of 19. It regulates the voltage (V) at the 11kV side with 1.25% tap-step over a tapping range of ±10% of nominal voltage. The bandwidth of the automatic voltage controller (AVC) is set as 3% (±1.5%). 11kV voltage (*Point of Coupling - PoC*) is regulated by SG1 to 1p.u. SG2 operates at unity power factor and supports V only during disturbances. The system is modelled using DIgSILENT PowerFactory software. Three 11kV feeders, with embedded generators on Feeders 1 and 3, are modelled together with fixed-tap low-voltage (LV) 11/0.433kV transformers. Depending on the load size, rating of LV transformers varies between 0.5-2.5MVA with 4-6% impedance. The LV loads (1 MW) and the converter-connected micro-generation (125kVA) are represented as lumped equivalent and loads/generation are assumed to be evenly distributed along each LV feeder. For the base case it was assumed that the network load is equal to generation (11MW, 100% load) and all the loads are modelled as static load (100%SL). SL are modelled as constant power loads for the V range between 0.7-1.2 p.u. and as constant impedance for voltages outside this range. For dynamic load representation two sizes of induction motors (IM), 30 and 250kW, are used in order to distinguish between domestic/ commercial/small industrial loads (on Feeders 1 and 2) and large industrial loads (on Feeder 3). The disturbance is a 500ms, balanced, upstream or Feeder 2 fault with Z_{fault} varied (except in Fig.9 and Fig.11) such that PoC V is 50% at fault clearance. This paper builds on the results presented in [1] and investigates the influences of operating conditions and proposes corrective actions to improve V stability of the DNC.

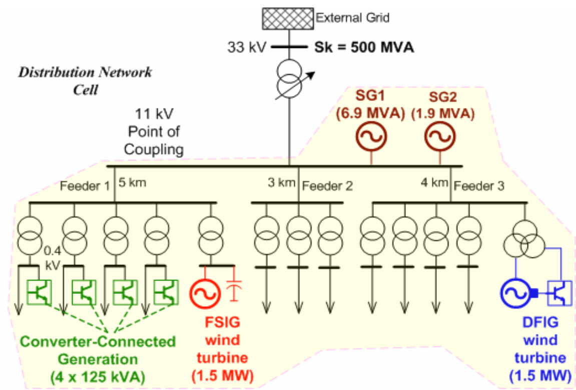

Fig.1 Single-line diagram of the distribution network cell with RES

INFLUENCE OF OPERATING CONDITIONS

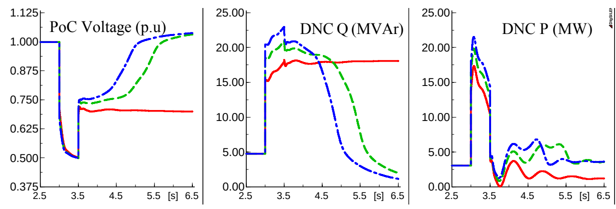

Fig.2 Influence of external grid strength on PoC voltage profile. Solid – Weak (S_k/2), Dashed – Base value (S_k), Dash-dot – Strong (2 S_k)

The DNC with RES can be formed in rural areas where the network is rather weak and RES are abundant. Alternatively, it could also be formed in highly interconnected strong power systems, such as cities where CHP and other building integrated RES (e.g. PV, rooftop wind turbines) can be installed. The strength of the external grid can be determined by the short-circuit power, S_k, and influences significantly the transient voltage stability of the DNC as shown in Fig.2 where a 0.5s, 50% sag occurs at t=3s inside the DNC. For a given S_k, (=500MVA, at 33kV) the V recovers in 3s, whereas for a weak network, S_k/2, it collapses. With a strong system, 2S_k, more active (P) and reactive power (Q) can be provided by the grid for the same disturbance and recovery is much better (1.5s).

A large variety of generation scenarios are considered as depending on season and time of the day, the generation profile of a network could change drastically. Any one or a combination of the above DG could dominate the network generation and thus significantly alter the response of the DNC. For example, during calm and sunny weather the network could be dominated by the PV generation whereas at night, wind generation (consisting of both FSIG and DFIG) may be the dominant source of power. Penetration of different type of DGs is simulated according to Table I where X corresponds to DFIG, FSIG, or CCG. The output of the DG of the type X is increased and at the same time the output of the SG is reduced (i.e., SG is replaced by X), as shown in the table, such that the total generation in the DNC is kept at 11MW. (e.g. case *DFIG3* represents the scenario where both gas turbines (SG) are disconnected and DFIG output is increased by 7.5 MW, i.e., 5 more DFIG based wind generators are added).

TABLE I PENETRATION OF DIFFERENT TYPES OF DISTRIBUTED GENERATION

Case	SG1 (MW)	SG2 (MW)	X
G1	6	1.5	***Unit rated***
X1	4.5	0	+3 MW
X2	0	1.5	+6 MW
X3	0	0	+7.5 MW

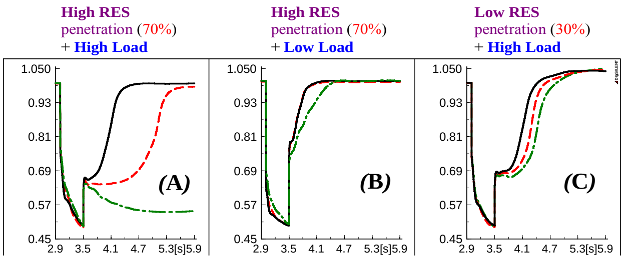

Fig.3 Influence of generation penetration and type on PoC voltage profile for varying grid conditions. Solid – DFIG, Dashed – CC, Dash-dot – FSIG.

In Fig.3A an *X3* scenario is assumed with load size at 100% consisting of 100% IM. Addition of more FSIG wind turbines destabilises the system since FSIGs stress the system further by absorbing Q following a fault. If more CCG is added to the system, the V recovers even though 70% of the generation (8MW CCG) is lost during the fault. Compared to FSIG, even though there is a lack of P, grid compensates for this loss, no instability occurs and voltage recovers. The best performance is obtained with large penetration of DFIG type DGs since DFIG regulates P and Q smoothly. The influence of generation type becomes less significant if the load is smaller. Fig.3B shows exactly the same case as Fig.3A except that the load is halved this time. Even though CCG trip, it does not make much difference since the load is picked up by the grid. The influence of FSIG is also reduced. Low penetration high load scenario, *X1*, (shown in Fig.3C) illustrates further the influence of the type of RES. Comparing with Fig.3A, the level of DFIG penetration does not influence much the V profile however, as the FSIG and CCG penetration increases the performance of the network gets worse due to Q consumption and P loss, respectively.

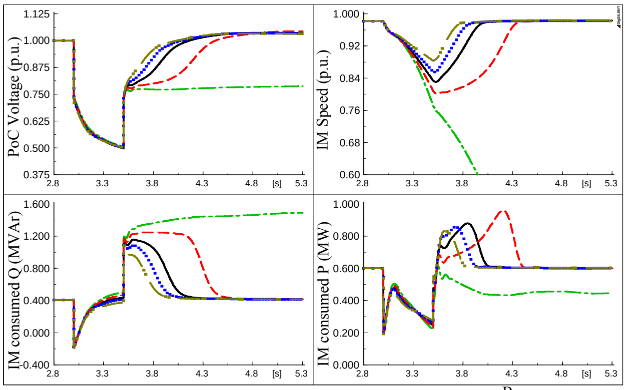

Fig.4 Influence of motor load characteristic, $T_{mech} = \omega_m^B$, on voltage recovery. Dash-dot – constant T_{mech}, Dashed – linear (B=1), Solid – B=2, Dotted – B=3, Dash-dot-dot – B=5.

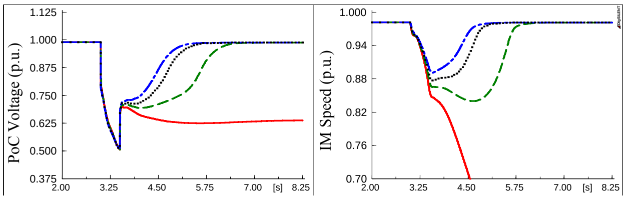

Fig.5 Influence of motor inertia, H, on voltage recovery. Solid – 0.8H, Dashed – H, Dotted – 1.2H, Dash-dot – 1.5H.

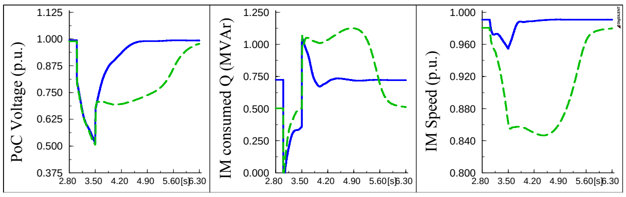

Fig.6 Effect of IM loading on V recovery. Dashed – 100%, Solid –50%.

When the dominant load in the DNC is IM, the recovery dynamics are important. Fig.4 shows the effect of IM mechanical torque, T_{mech}, characteristic. Worst case occurs for constant T_{mech} (due to fast stalling) and for higher exponential coefficient the recovery is better since T_{mech} reduces as the IM speed drops. Consecutively this reduces deceleration rate and Q consumption.

IM inertia (H) is also important, as shown in Fig.5. Higher H results in lower acceleration, and consecutively lower Q consumption. In this case DNC is on the verge of instability. Even very small changes in P/Q could cause significant V variations. In other cases though, IM inertia may not be so influential.

The IM operating point also affects V recovery immensely, as shown in Fig.6. When loaded at 100% the load consists of 25 IM (rated at 30kW) and operates at rated power. In the case of 50% loading, the IM number is doubled (50) so that same P (0.75MW) is drawn from the grid. At 50% loading, due to higher number of machines, total Q of the IM is higher than the 100% loading case. However, the speed is closer to the ω_{syn} and, more importantly, T_{mech} is much lower, hence deceleration from ω_{syn} is small and Q consumption during/after the fault is less resulting in better V recovery for the same sag.

MITIGATING INFLUENCE OF DG CONTROL

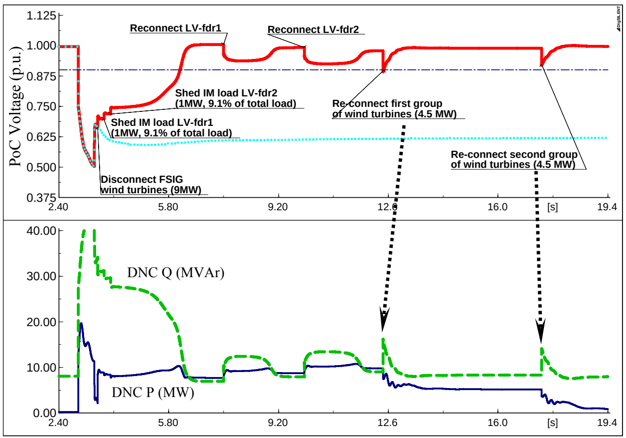

Fig.7 Influence of load/FSIG shedding on V recovery (Dotted - no shedding)

FSIG and IM cause voltage instability by the re-magnetisation process following a sag. These could be shed temporarily and be reconnected when the V is recovered. Such a shedding scheme (for a fault inside DNC) is shown in Fig.7 with labelling of appropriate events. FSIG wind farm is tripped if V<0.7 p.u. for 600ms. Next, the IM load is shed until V≥0.75 p.u, with 200ms breaks, (in this case 2 LV feeders, 18% of total load is shed). Once the V is recovered the load is restored very fast within a few seconds (see Fig.7). Following this, FSIG wind farm is re-connected in two groups. Instead of direct connection, wind power can be ramped-up by the pitch control resulting in a smoother transfer. Nevertheless the V is kept above 0.9p.u.

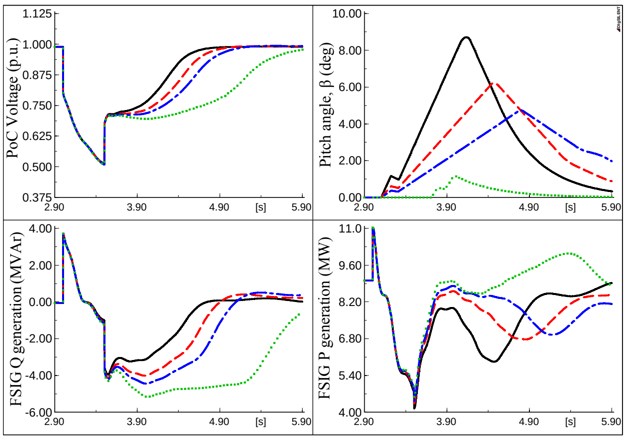

Fig.8 Influence of FSIG pitch control on voltage recovery. Dotted – Minimum pitch, Dash-dot – dβ/dt=3deg/s, Dashed – dβ/dt=5deg/s, Solid – dβ/dt=10deg/s.

Rather than disconnecting the wind farm, pitch control can be utilised to reduce Q consumption (see Fig.8). Minimum pitch action corresponds to the case where there is a 0.5s delay and controller gain is low. Other cases illustrate the situations with optimised gain and different angle rate changes. As the rate increases, P_{wind} is reduced faster resulting in less acceleration and ultimately, less Q consumption and better V recovery.

In addition, FSIG compensation also affects immensely the DNC performance (see Fig.9). When a similar rated Statcom is utilised instead of a SVC, the reactive current injection is kept at maximum (1p.u) compared to the linear drop of current with V in SVC. With Statcom, Q injection is higher and if it can be overloaded by a few seconds recovery gets slightly better at the expense of higher cost.

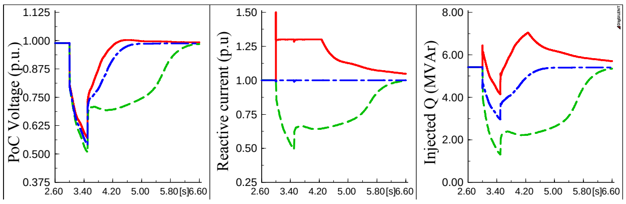

Fig.9 Influence of FSIG compensation. Dashed – SVC, Dash-dot – Statcom, Solid – Statcom (30% overload).

Rather than using an FSIG, limited variable-speed IG with external rotor resistance, R_{ext}, can be used [2]. The controller increases R_{ext} (=R_{rotor}) during a fault (see Fig.10) and changes the torque (and Q) characteristic. This provides a more stable operating region for IG and reduces Q consumption immediately after the fault.

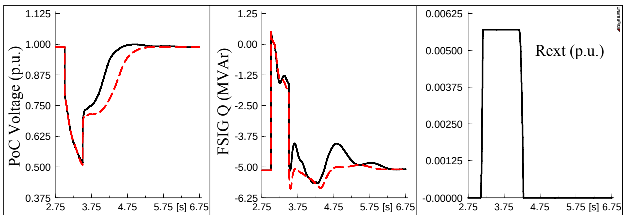

Fig.10 Influence of R_{ext}. Dashed – no R_{ext}, Solid – With R_{ext} = R_{rotor}

DFIG-based wind farm can control Q exchange dynamically and support V within the device limits and using different combinations of rotor-side (RSC) and grid-side converters (GSC) as suggested in [3] (see Fig.11). DFIG operates at rated power and converters (rated at 0.5MVA) can be overloaded by 20% for a few seconds with P prioritisation. When only RSC is used for V control, it is almost fully loaded with active current (i_{qr}) and magnetisation of the DFIG. There is no margin to inject additional reactive current (i_{dr}) for Q generation. Hence there is only a slight improvement in V (even though Q is amplified by 1/slip) with RSC only compared to the unity pf case. When magnetisation is provided by RSC and only GSC is used for V control, the improvement is better because GSC has more Q margin than RSC (rated rotor P is 250kW). Alternatively V support can be provided using both converters according to the grid code [4], which allows P reduction in proportion to the retained V (i.e. higher margin for Q) resulting in a much better recovery. When reactive current is prioritised over the torque producing current, Q is boosted, and V recovery is slightly improved however, uncontrolled P reduction may cause frequency regulation problems in weak networks even though P might be quickly restored following the sag.

During the sag, the GSC of the CCG is limited to export P and as a result V_{DC} increases and causes the CCG to trip. In order to prevent this, either a dc-crowbar resistance with a chopper can be installed [2] or P feeding into the DC-link (source P) can be reduced [5]. In any case V_{DC} can be contained within limits and CCG can ride through the sag. Depending on different P/Q control schemes, V recovery can be improved as shown in Fig.12. It is assumed that the converters are 10% oversized in order to accommodate steady-state V variations and can be overloaded by 20% for a few seconds. The case of V control with prioritising P is arranged such that GSC injects 1 p.u. active current (in this case i_{dr}) and Q is generated by overloading the converter by 20% (i.e. 0.66 p.u reactive current). The case of Q prioritisation corresponds to the case where the P source (e.g. solar panel, fuel-cell) is blocked and the GSC is operated as a Statcom.

The Q generation in the DNC can also be improved if the over-excitation limit of SG is relaxed. Fig.13 compares the case where field voltage limit, E_{fd}^{lim}, is increased from ±4 p.u to ±4.5 p.u. Field circuit is overloaded for a few seconds however, the V recovery is considerably better and in certain cases this may even prevent V collapse.

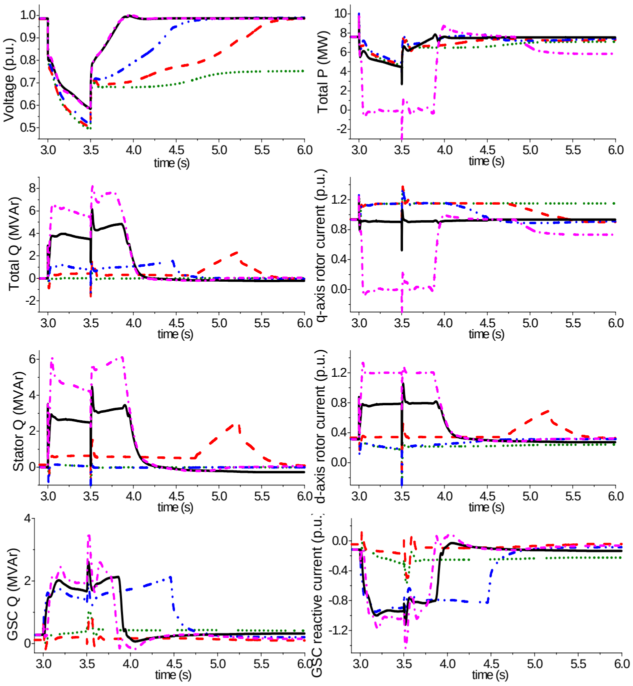

Fig.11 Responses of different DFIG V control schemes. Dotted – Unity pf, Dashed – RSC only, Dash-dot-dot – GSC only, Solid – coordinated RSC and GSC according to grid code, Dash-dot – Reactive power prioritisation.

CONCLUSIONS

External grid strength, which depends on its location, is an important factor in determining V stability of DNC. High FSIG and CCG penetration makes V recovery worse due to Q consumption and P loss, respectively. DFIG penetration does not significantly affect the V performance of DNC. IM mechanical torque (T_{mech}) plays an important role during faults as it affects the IM stalling. Higher IM inertia offers less deceleration and better V response. When IM is loaded less, it decelerates less and absorbs less Q (thus faster V recovery). FSIG and high load are the cause of V instability and they may be shed following a fault to prevent V collapse and reconnected fast within a few seconds. Utilising improved pitch control of FSIG wind farm improves DNC transient response. FSIG compensation is important for V stability and Statcom provides better response than SVC. DFIG can supply Q using different combinations of converters and significantly improve the transient V response of DNC. CCG can be provided with additional equipment so that it rides through a fault and, with different control algorithms, can provide Q support improving V recovery immensely. Relaxing SG over-excitation limit, may also improve V response considerably.

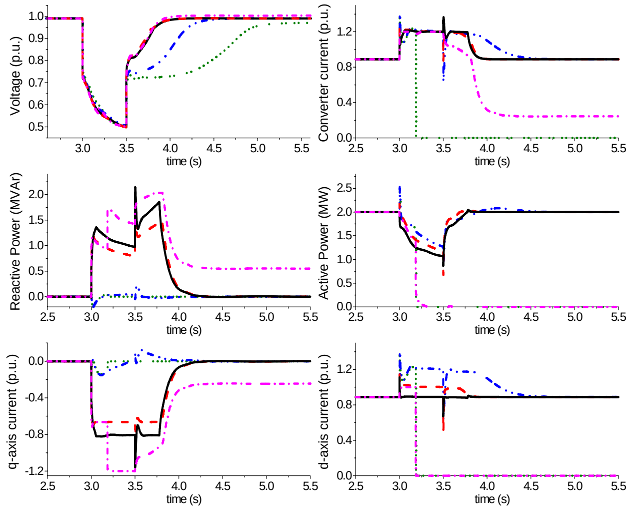

Fig.12 Responses of different CCG ride-through and V control schemes. Dotted – Trip, Dash-dot-dot – Unity pf, Dashed – V control prioritising P, Solid– V control according to grid code, Dash-dot– Q prioritisation (P=0)

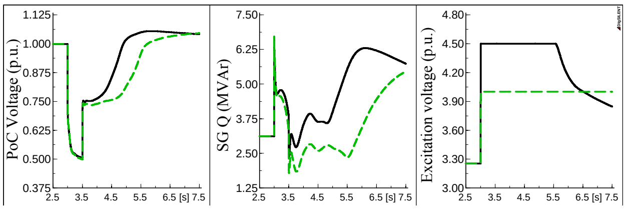

Fig.13 Influence of SG excitation limits on voltage recovery. Dashed – E_{fd}^{lim} = ±4 p.u., Solid – E_{fd}^{lim} = ±4.5 p.u.

Acknowledgments

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