Rate of Change of Frequency
DS3 Advisory Council Discussion Paper

1 Purpose

The purpose of this document is to provide information for discussion on the rate of change of frequency (RoCoF) issues facing the Ireland and Northern Ireland power system. There are various approaches that could be used to mitigate the problem. This paper aims to provide sufficient background to the members of the DS3 Advisory Council to enable a discussion on the relative merits of different approaches to the problem and to provide recommendations to the most effective approach.

2 Background

Traditionally power systems have been developed with generating units which are all electrical locked into coherent phases, physically rotating at the same effective speed, creating a uniform behaviour known as a “synchronous system”. This results in a nominal operating frequency, usually 50Hz or 60Hz. This nominal frequency is a measure of the electric energy balance in the system. When supply and demand are in balance, the frequency will be constant. If there is excess generation, the frequency increases; conversely, if there is insufficient generation, the frequency will decrease (the synchronous units in unison will all speed up or slow down as required). The management of this frequency balance is a core remit of the Transmission System Operators, EirGrid and SONI.

Classically, frequency has been managed within strict tolerances (less than ±2% or less in larger interconnected power systems). Following the loss of a large unit, frequency will in the first instance decrease rapidly. As the frequency falls generators will increase their output under automatic governor control strategies to help address the energy imbalance. Synchronous generators also provide a so-called ‘Inertial Response’, which is a surge in output power due to a transformation of rotational kinetic energy into electrical energy while the machine is decelerating. In addition, the natural fall in demand with falling frequency will help arrest the decline. Failure to manage the frequency within tight tolerances would result in irreparable damage to generators and as such protection devices will disconnect all units in extreme frequency conditions leading to a power system blackout. High frequency events are also a possibility if a large demand (such as an interconnector exporting at a high level) trips. Therefore prudent system operation requires that any single likely event does not lead to one of these situations arising. This is challenging when the loss of one large plant can represent up to 15% of the total generation in the system.

Prudent system operation requires ensuring that there is a balance of complementary responses following the loss of a large unit to ensure the frequency remains within these tight tolerances. With increased wind generation this response becomes more challenging. To this end, various issues with ensuring the frequency remains within these tight tolerances are being addressed in the DS3 Frequency Control workstream.

Notwithstanding this, following detailed technical analysis of the Ireland and Northern Ireland power system and a review by international experts and representative industry and academic peers, EirGrid and SONI have determined that there is an additional challenge to operating the power system during these type of events, namely the Rate of Change of Frequency (RoCoF), that could, if not addressed, lead to unacceptable risks to the power system. Rate of Change of Frequency is determined by the size of the power imbalance on the system and the inertia of the power system. Larger imbalances result in a higher RoCoF, while higher inertia levels result in a lower RoCoF. With the expected increases in non-synchronous generation (which does not contribute to synchronous inertia), it is expected that the RoCoF levels on the system will rise.

Without addressing the challenges associated with RoCoF, which are described in the next section, it is likely that there will be a requirement to limit the output of windfarms. EirGrid and SONI believe that a programme of work can be developed which when implemented will systematically address these challenges and remove RoCoF as an issue which could limit the level of non-synchronous generation in the Ireland and Northern Ireland power system.

3 The Challenges

The largest infeeds on the Northern Ireland and Ireland power system over the next decade will remain a significant percentage of the total generation. With the increase of wind power plants the synchronous on-line inertia in the power system could be significantly lower than on today's system[1]. The challenges faced by the TSOs are as follows:

a) The frequency will initially fall faster (higher RoCoF) following the loss of a large infeed in a system with less synchronous inertia. It has been found that at the increased levels of Rate of Change of Frequency (RoCoF) expected with increased wind generation, not all generation (wind and conventional) may stay synchronised during a loss of large infeed event.

b) A severe fault near a large cluster of windfarms could cause a significant temporary active power imbalance on the system. This could be made worse if windfarms do not recover their active power quickly after the fault is cleared. The FOR study showed that such events could lead to very high RoCoF values leading to cascade tripping of plant and blackouts.

c) Separately, the protection equipment utilised on the distribution network for detecting isolated networks, may also operate to disconnect all distribution-connected generators for high values of RoCoF.

d) A fourth potential issue could be a large positive RoCoF if a large demand tripped or an interconnector tripped while exporting large amounts of power to Great Britain. If the resultant high frequency led to a substantial loss of generation, then this could lead to a large negative RoCoF, and possible system instability. This scenario was not specifically considered as part of the FOR study.

Any of these cases could result in the loss of significant levels of additional generation (i.e. cascade tripping) which would, in all probability, lead to a system blackout.

A prudent system operator could not knowingly operate a power system where these scenarios were likely to unfold. The TSOs would limit the level of windfarm plants on the system to ensure that potential RoCoF never exceeds unacceptable levels that would result in system instability or potentially a blackout. However, this aggregate operational limit would likely lead to levels of curtailment that would materially impact on efficiently meeting the 2020 RES targets.

The objective is to develop an operational strategy and system capability that allows operation at high levels of wind power plant output without leading to a system risk with respect to high RoCoF.

[1] "Ensuring a Secure, Reliable and Efficient Power System in a Changing Environment", EirGrid, June 2011

4 Studies and Analysis – Key Results

EirGrid and SONI published the results of the Facilitation of Renewables (FOR) study in 2010. The FOR study considered frequency and RoCoF issues for a wide variety of scenarios. The results of the study are of concern to EirGrid and SONI, as they showed potentially high values of RoCoF in high wind scenarios. The values being seen in the study were two orders of magnitude greater than the current Grid Code RoCoF standard of 0.5Hz per second. Figure 1 shows a plot of RoCoF values versus System Non-Synchronous Penetration (SNSP) for every different contingency and dispatch scenario in the FOR study. RoCoF values in excess of 0.5Hz per second were seen quite commonly in many of the high wind scenarios studied. If such values were encountered on the power system, they could potentially lead to the loss of some or all generation connected to the system.

Figure 2 and Figure 3 show the RoCoF values that result from two different contingency types: loss of largest infeed contingencies; and voltage-dip induced frequency dips from lost power from wind generation. Loss of largest infeed contingencies traditionally lead to a frequency dip and are well known. The voltage-dip induced frequency dip was brought to light during the FOR study. Voltage dips near a cluster of windfarms could cause windfarms to significantly reduce their power output for a period of time, e.g. 100ms-1s, depending on the duration of the fault, and the speed of active power recovery from the windfarm. In Ireland and Northern Ireland, where large numbers of windfarms are connecting to parts of the network, this type of fault could potentially have serious ramifications.

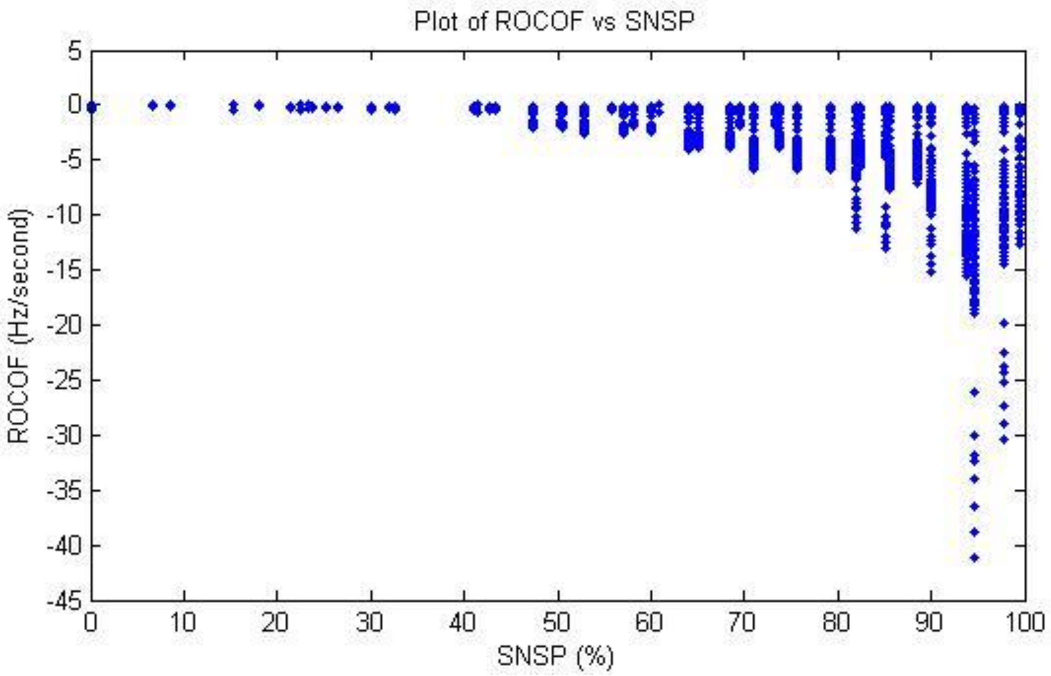

Figure 1: RoCoF vs SNSP for all applied contingencies (FOR Study). Each point represents a different dispatch scenario / contingency combination

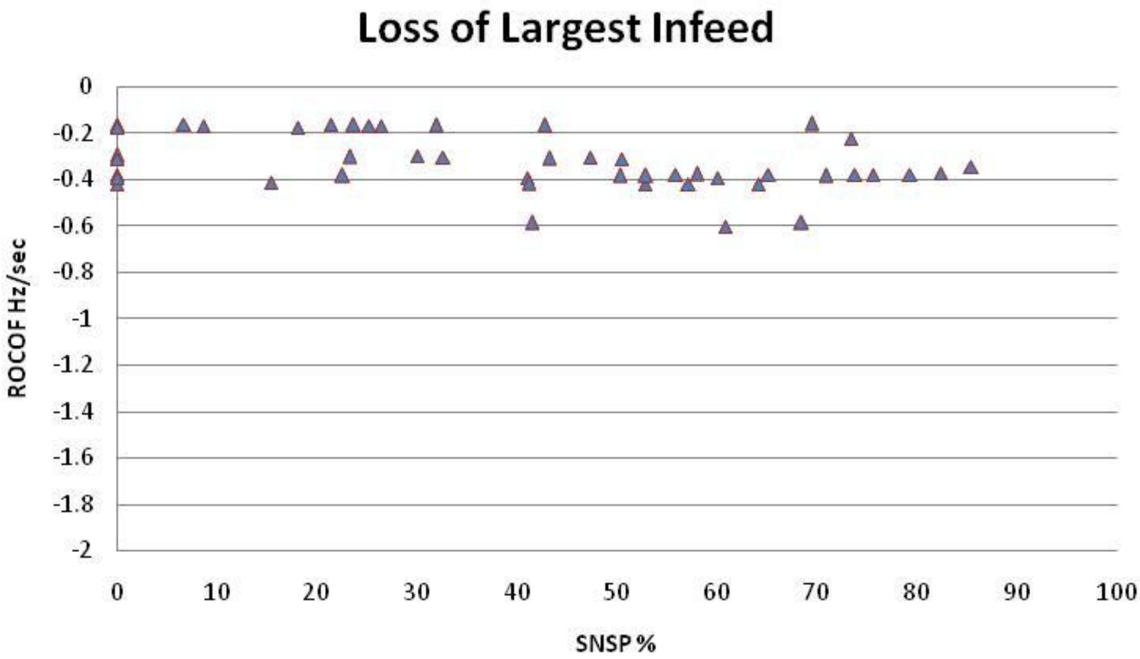

Figure 2: RoCoF vs SNSP for loss of largest infeed only (FOR Study). Each point represents a different dispatch scenario

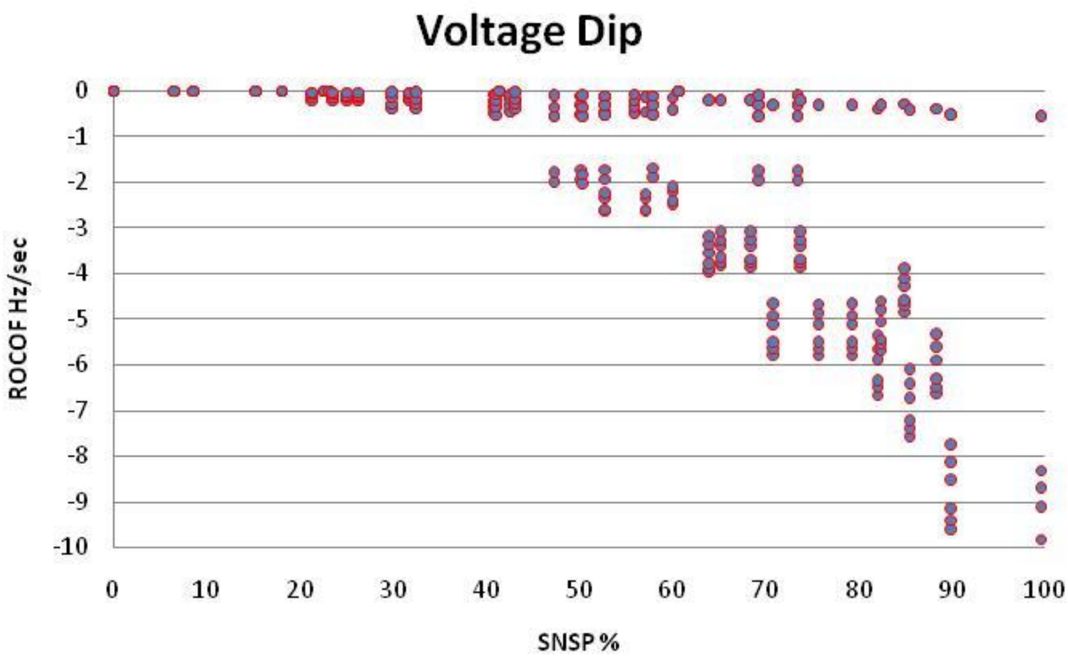

Figure 3: RoCoF vs SNSP for Fault-induced Frequency Dips (FOR Study). Each point represents a different dispatch scenario

5 Resolving the RoCoF Issues

There are different approaches to resolving the RoCoF issues, and they are not necessarily mutually exclusive. We consider solutions to each of the RoCoF issues in turn.

5.1 Resolving the RoCoF issue: Loss of Largest Infeed

At present on the Ireland and Northern Ireland system during times of high wind, RoCoF values of up to 0.5Hz/s are being seen for the loss of a large infeed. The two broad approaches to this are set out below.

Ensure all generation can tolerate higher ROCOF values

During high rates of change of frequency there will be considerable forces and acceleration placed on the foundations, shaft and auxiliaries of a generator. While these have never been a limit before, it was in a context where it was considered unlikely that a RoCoF in excess of 0.5 Hz/s would ever be experienced on the power system. With the increase in wind generation, this is no longer the case. As prudent system operators there needs to be greater clarity on what the limiting RoCoF value is and the technical limits of both conventional and wind plant in this regard. Subsequent to this, an operational RoCoF standard can be established.

Ensure system inertia is such that RoCoF does not exceed 0.5Hz/s

The second approach is simply to keep sufficient inertia on the system so that RoCoF values do not exceed 0.5Hz/s (or some higher value that is acceptable). This could be done in several ways, though some overlap between these potential solutions would be expected.

1. Maintaining a certain amount of conventional machines on at all times, assuming no change to their minimum generation levels. This would have implications for dispatch including, potentially, curtailment levels of wind, although it would depend on the approach taken.
2. Examine the minimum generation levels of generators and see if they could be lowered while still providing necessary system services such as frequency response and frequency regulation.
3. Incentivise new entrant machines with higher synchronous inertia to connect to the system.
4. Develop network solutions to the RoCoF issue, i.e. plant that could be added to the network to provide synchronous inertia. The main plant types would be synchronous condensers or flywheels. Synchronous condensers are essentially synchronous loads with similar reactive power capability to synchronous generators, and so provide synchronous inertia and dynamic voltage support to the network. As part of the DS3 programme, a desktop study will be done to establish the capital cost requirements for this solution.

Based on the FOR study[2] results, an increased Grid Code RoCoF standard of up to 1Hz/s would be adequate to cover off the Loss of Largest Infeed RoCoF issue (see Figure 2). Note that the maximum largest single infeed could at times increase to 500MW when the East-West Interconnector is commissioned. Also, large generators in excess of 500MW could potentially connect in the future. Note that the FOR study assumed full Grid Code compliance of all machines based on theoretical models. It would be prudent therefore to include some safety margin in any new agreed RoCoF standard to allow for modelling errors.

The ENTSO-E draft network code[3] has a RoCoF standard of 2Hz/s for generators. Assuming this does not change in the next few months, this value will become the standard in Ireland and Northern Ireland.

[2] Facilitation of Renewables Study, EirGrid, 2010

[3] https://www.entsoe.eu/resources/network-codes/

5.2 Resolving the RoCoF issue: Voltage-dip Induced Frequency Dips

This is the most problematic of the ROCOF issues. The FOR studies indicated that very high ROCOF values (up to 50Hz/sec in some scenarios) could occur if a cluster of windfarms were to be subjected to a severe fault, based on the wind installed by 2020. This issue is being addressed through improving fault ride-through standards on windfarms. Specifically, Grid Code modifications will be developed that mandate active power to recover within 500ms of the voltage recovering after a network fault. The modifications will be aligned with the ENTSOE draft network codes.

Separately, more detailed studies (DS3 modelling and studies workstream) will be carried out to determine if this is likely to be an issue in the near future, based on current levels of installed wind. If improved fault-ride through standards can be implemented and verified on windfarms, then this issue should become less problematic. However, further studies will be carried out based on these improved standards to ensure this issue can be addressed.

5.3 Resolving the RoCoF issue: Anti-Islanding ROCOF Relays

The DSOs are working to establish what increased ROCOF limits are acceptable, or whether time-delays can be added to ROCOF relays. Another approach would be to change the anti-islanding protection philosophy to avoid using ROCOF-type relays completely. It could be possible to use existing phase-angle drift or vector-shift methods to detect if an island has been formed.
It appears likely that a solution will be found to this issue in the near future, though there may be cost implications if relays need to be replaced, or if substantial resources are required to change relay settings.

5.4 Concept of Emulated Inertia

'Emulated inertia' from wind turbines or other non synchronous plant is a form of fast-acting frequency response. However, the frequency needs to have dropped before an inertial-type active power boost is provided. In other words, the very high RoCoF value can occur before the emulated inertial control is activated. Emulated inertia could be useful in mitigating frequency nadirs that occur during a system event, but it is not the same as the synchronous inertial response provided by synchronous machines[4,5].

5.5 Summary

As outlined above, the RoCoF issue is multi-faceted and will in all likelihood require a set of co-ordinated solutions. Further detailed analysis is required to properly assess whether these potential solutions, taken together, will appropriately resolve the issue. In the sections below, the actions that the TSOs intend to initiate in this regard are outlined.

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[4] G.Lalor, A.Mullane, M.O'Malley, "Frequency Control and Wind Turbine Technologies", IEEE Trans. Power Systems, Nov.2005

[5] L.Ruttledge, D.Flynn, "System-wide inertial response from fixed speed and variable speed wind turbines", IEEE PES July 2011

6 Further Investigation

While there are potential solutions to the different RoCoF challenges, many of which appear to have merit, further investigation will be required.

International Review

EirGrid/SONI will contact other island TSOs in order to see if other small power systems have experienced high values of RoCoF, or can offer any data on machine performance during high RoCoF scenarios. Machine manufacturers may also be able to offer data that is of value to this workstream.

Potential Demonstration Projects

Under the auspices of the DS3 programme, EirGrid and SONI will be seek industry partners in demonstration projects that will help provide data on key aspects of the RoCoF challenges. Potential demonstration projects could include:

New Test Trials for Generators

EirGrid group would be interested in hearing from any generators that would like to propose ways for testing or demonstrating the RoCoF capability of generators.

Windfarm Emulated Inertia / Frequency Response

Although emulated inertia will not help the RoCoF issue directly, it would be useful to obtain real field data on the performance of windfarms in various frequency response modes which could be of considerable value to the system.

Alternatives to Anti-Islanding RoCoF Protection

The DSOs are discussing changes to the anti-islanding RoCoF protection installed on distribution windfarms. There may be scope to run demonstration projects on different anti-islanding philosophies, done in conjunction with the DSOs.

7 Implementation Phase

Solving the RoCoF issue will take time: time to reach agreement on the approach, time to implement the changes to Grid Codes/relays/equipment, and time to verify that the RoCoF issues have been closed off in the context of operational policy. The implementation of solutions to the RoCoF issues will also depend upon the results from the further investigation carried out by EirGrid and SONI on international experience of RoCoF, and on input from equipment manufacturers.

Reaching Agreement / Grid Code Changes

A Joint Grid Code Review Panel Working Group is being set up to consider RoCoF and other issues related to the DS3 programme. This group will bring together the various stakeholders in order to find an agreed value for the RoCoF standard. This group will then recommend the necessary changes to the Grid Codes in Ireland and Northern Ireland.

Generator Testing

When the Grid Code changes are made, it will be necessary for generators to confirm their ability to meet the increased RoCoF standard.

Tests will also be carried out on minimum generation levels, and whether machines can still provide system services at new lower minimum levels. There will also be ongoing performance monitoring of plant performance with respect to the Grid Codes.

RoCoF Protection Changes

The DSOs are currently investigating if RoCoF relays can be adjusted to trip at higher values of RoCoF, or if different protection philosophies can be used to provide the necessary anti-islanding protection for distribution plant. There may be a substantial cost in terms of capital and man-hours imposed by these necessary changes. The DSOs will determine what this cost could be, and how long it would take to change all of the RoCoF relay settings on the system.

New WFPS Standards

The DS3 workstream on voltage control is developing a set of universal standards for windfarms, with input from TSOs and DSOs in both Ireland and Northern Ireland. These new WFPS standards will help address the issue with voltage-dip induced frequency dips, as they will ensure that windfarms recover their active power output quickly following a voltage dip.

Studies & Operational Policy Review

The operational policy on SNSP will be reviewed at six-monthly intervals, and will take into account information from analysis of the system during periods of high wind generation, and any other developments in the implementation phase of the DS3 RoCoF workstream.

8 Upcoming Actions

- Joint Grid Code Working Group
- DSOs to review RoCoF protection
- Universal Windfarm standards document
- Call for Demonstration projects

9 Summary of RoCoF Worksteam Actions

Workstream	Area	Decision/Deliverable/Task	Responsible	Due by	Complete
RoCoF	Setting appropriate ROCOF standards on all generators	Bring ROCOF modification to the Grid Code Review Panel meeting	TSOs	31/12/2011	Yes
RoCoF	Setting appropriate ROCOF standards on all generators	Identify regulatory mechanism for implementing ROCOF standard in Northern Ireland	SONI TSO	31/12/2011	Yes
RoCoF	Setting appropriate ROCOF standards on all generators	Formal response from generators and wind farms to modification	All generators	31/12/2011	Superseded
RoCoF	Setting appropriate ROCOF standards on all generators	Establish DS3 Grid Code Working Group	TSOs / Industry	31/03/2012	No
RoCoF	Setting appropriate ROCOF standards on all generators	Working group develops proposals on ROCOF standards for Conventional and Wind Generators	TSOs / Industry	30/06/2012	No
RoCoF	Setting appropriate ROCOF standards on all generators	Review of Working Group summary paper	TSOs	30/09/2012	No
RoCoF	Setting appropriate ROCOF standards on all generators	Modification approval by GCRP	TSOs	30/09/2012	No
RoCoF	Setting appropriate ROCOF standards on all generators	Bring modification to appropriate fora for Northern Ireland	SONI TSO	30/09/2012	No
RoCoF	Setting appropriate ROCOF standards on all generators	Approve modification to Grid Code and Distribution Code	CER	31/12/2012	No
RoCoF	Setting appropriate ROCOF standards on all generators	Approve modification to appropriate regulatory instrument	NIAUR	31/12/2012	No
RoCoF	Setting appropriate ROCOF standards on all generators	Review and Implementation of new standards	TSOs / DSOs / Industry	31/12/2013	No
RoCoF	Ensuring appropriate ROCOF on distribution protection	Kick-off and scope TSO-DSO ROCOF working groups	DSOs / TSOs	31/12/2011	Yes
RoCoF	Ensuring appropriate ROCOF on distribution protection	Examine safety implications and security impact on changes to G10, G59 protection settings including ROCOF and voltage	DSOs	30/06/2012	No
RoCoF	Ensuring appropriate ROCOF on distribution protection	Provide written report on implications for ROCOF setting to loss of mains protection including implementation strategy	DSOs	30/06/2012	No
RoCoF	Ensuring appropriate ROCOF on distribution protection	Decision on change to ROCOF protection settings	ESB Networks	30/09/2012	No
RoCoF	Ensuring appropriate ROCOF on distribution protection	Decision on change to ROCOF protection settings	NIE	30/09/2012	No
RoCoF	Ensuring appropriate ROCOF on distribution protection	Review and Implementation of new standards	TSOs / DSOs / Industry	31/12/2013	No