The Role of Grid Codes in Isolated Power Systems

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***Abstract*— Small isolated power systems supplying peak demand levels between 1 and 100 MW possess unique characteristics that have to be considered when integrating VRE resources. These systems are mostly based on diesel generation with high generation cost, which makes the integration of VRE in general and PV in particular economically interesting. Very high instantaneous non-synchronous penetration levels can however be reached very quickly, and the combination of that and the low-inertia, low stability characteristics of such systems and the fact that most systems are operated at a very low level of automation can be difficult. Small VRE generators which would be connected to the distribution grid in larger systems must often fulfil comprehensive technical requirements that are only applied to larger installations in larger systems. The development of such requirements, their enforcement and the procurement of suitable equipment at competitive cost are often a major challenge to the operators of isolated power systems, especially in developing countries where such systems are most prevalent.**

***Keywords*— PV, VRE, island power system, isolated power system, grid code, distribution code, off-grid, grid-forming.**

I. Background

Isolated power systems, supplying a town, village or even only a few households, can be found all over the world in places where access to a larger power system is either impossible or economically infeasible. These are usually either remote locations in sparsely populated areas with a low load density which does not warrant large-scale grid expansion, or systems located on islands which are either too small or too remote to justify the construction of sub-sea cables. Such conditions are predominantly found in developing countries in tropical areas. The hot spots of small isolated power systems with peak load values between a few kilowatts and a few megawatts are sparsely populated areas on the African continent and islands in South East Asia and the Caribbean. This paper is focused on remote power systems in these areas with peak load values between 1 and 100 MW and based on work conducted by Energynautics in Indonesia, India and the Caribbean.

Power generation in small isolated power systems, especially in tropical areas, is typically provided solely by diesel generators. The cost of electricity in such systems is high due to the fuel cost and the high maintenance efforts required especially for small high-speed diesel generators. As economy of scale has led to a stark reduction of PV panel and inverter prices over the last two decades, PV now presents itself as an economically feasible alternative to diesel generation. Tropical countries usually have moderate to high solar potential, and PV can usually generate at a lower cost than diesel generators, especially in more remote areas, where fuel is even more expensive due to transportation cost.

Small power systems are inherently less stable and more sensitive to disturbances than larger interconnected systems and can reach significant VRE penetration levels very quickly. VRE generation, mostly PV, must hence be capable of contributing to system stability, especially in the frequency control domain, and be set up accordingly. Technical requirements for generators, as specified in the grid codes in larger systems, have to be tuned to the characteristics of the power system. Since each small isolated system has its own characteristics and operational principles, separate development of requirements for each single system can impose an undue financial burden on the system operator. Developing grid codes applicable to different systems with different characteristics is however also challenging. The role of grid codes and alternative ways of providing uniform requirements wherever possible, which can significantly reduce the additional cost of VRE development in such systems, will be investigated in this paper.

II. Project Experience

The authors have based this paper on work experience reviewing and partially revising or re-designing the following grid codes, which are either entirely or partially applicable to isolated power systems:

- Distribution code [1] and Renewable Energy Connection Guideline [2][3] of Indonesian state utility PLN, theoretically applicable to more than 600 systems on islands and in remote areas of Papua and Kalimantan;
- The Grid Code published and applied by The Barbados Power & Light Company Ltd. [4], applicable to all generators in the power system of Barbados;
- Technical regulation in place in 2015 with the Public Utilities Corporation of the Seychelles [5], and their grid code draft published in 2018 [6] (not developed by Energynautics);
- The Grid Code and Distribution Code published and applied by the Energy Regulatory Commission of the Republic of the Philippines [7][8], and the additional Small Grid Guideline published by the Philippine Distribution Code Committee [9];
- The grid codes and/or technical regulation of Malaysia, Thailand, Guyana and Trinidad and Tobago, reviewed at a high level.

Moreover, the authors have conducted several island system stability studies in Indonesia, the Seychelles, the Bahamas, Ecuador, Guyana and Trinidad & Tobago.

III. Current Status of Grid Codes for isolated Power Systems

From a regulatory and institutional point of view, isolated power systems can be classified into three categories:

- Power systems of island nations, which are typically operated by the national utility;
- Power systems in remote areas or on islands that are part of a larger nation and that are operated by the national utility or TSO/DSO, often with multiple such power systems under the governance of the same entity;
- Privately owned isolated power systems of any kind.

Island nations often already have some type of grid code, drafted by the utility, the regulator or the responsible government agency. These may however run into market power issues when the system requires unique characteristics from generators to maintain system stability, but the country's energy sector is too small to drive development of the corresponding technology. This issue is elaborated on in section VI.

Power systems under the governance of a grid operator also in charge of other and larger power systems are either subject to that operators' distribution or transmission codes, which often lack the specific requirements the systems need, or exempted from grid code applicability for that exact reason. Requirements for new generators are specified in PPAs for IPP generation case by case, and only very few countries (notable: Philippines) have separate code documents for isolated systems in place.

IV. Technical Characteristis of Isolated Power Systems

Isolated power systems supplying peak load in the megawatt range typically show the following characteristics:

- Single or very few conventional generation sites supplying the load;
- High share of reciprocating engine generators, mostly diesel (HFO or LFO), natural gas or biogas only in rare cases;
- Radial transmission and distribution grid with the primary voltage between 10 and 20 kV;
- Low stability and low security of supply due to small size and low inertia;
- Primary frequency control by the speed droop controllers of the diesel gensets and manual secondary control, resulting in relatively fast primary, but very slow secondary control response;
- High generation cost, as high-value imported fuels such as diesel are used.

Transmission grids with voltage levels of 70 to 150 kV can be found in some isolated systems with peak load values in the high megawatt range, and small coal power plants are also somewhat common on Southeast Asian islands, most of the usual technical characteristics however apply for these systems as well.

The flexibility of diesel generators, which can be started within minutes, tolerate low output operation reasonably well and can provide ramp rate in excess of 100 % of rated power per minute can theoretically be used to integrate high shares of VRE generation without running into the inherent flexibility limits of the system. The accessibility and usability of this flexibility is however often limited quite drastically by the low degree of automation in dispatch and frequency control, and such systems typically do not take to short-term VRE fluctuations very kindly. While modern diesel generators connected to an energy management system (EMS) as part of a SCADA or mini-SCADA system can sufficiently balance out a high degree of even very short-term fluctuations, as evidenced by a number of operational small diesel-PV hybrid systems, most isolated systems do not have this option available, and the communication delays imposed by manual control can lead to further deterioration of the already low frequency quality and security of supply.

Short-term fluctuations on the other hand can be very high, especially for PV in tropical countries with frequently changing overcast situations. The small size of most isolated power systems does not allow for the wide distribution of VRE units that smoothens out system VRE feed-in in larger power systems. Distribution should however always be considered, as even splitting up the total PV capacity to as few as three or four sites can significantly reduce the magnitude of short-term fluctuations that need to be balanced. In essence, the conventional generators (or other flexibility sources) need to be prepared to cover changes in VRE output on two different levels:

- Short-term feed-in fluctuations in the time frame of seconds to minutes, induced by changes in wind speed or cloud movement, which happen frequently and are difficult to forecast;
- System wide output change events induced by diurnal feed-in patterns or singular events such as storm fronts, which can be larger in magnitude, but are easier to predict.

The level of short-term fluctuations that can be expected is largely determined by the size of the individual VRE installations, while the system wide output change events are determined by the overall installed capacity and the geographic size of the system.

V. Technical Requirements for Generators

Frequency control issues that are the most prevalent integration issue for wind and PV in isolated power systems can be mitigated by a variety of measures. As mentioned, the technical optimum would be the introduction of SCADA and EMS systems, and, to avoid excessive strain on the diesel engines and increase VRE share even further, the installation of battery energy storage systems (BESS). Despite the fact that both technologies are proven, commercially available and often economically feasible as well, utilities especially in developing countries often shy away from the higher initial cost. With often no previous experience with VRE on the system operator's side, starting directly with such a severe system transformation may also not be the most appealing idea. Starting out with lower VRE shares to allow utility staff to gain first operational experience and gather data may be desirable and result in a more sustainable development in the long run. The simpler the initial system is, the lower the risk of “starting with a failure” and providing yet another case that reinforces the common notion that “renewables may work in Europe, but not here.”

With this in mind, technical requirements for generators in isolated power systems become extremely important to the success of renewable integration. While certain flexibility issues encountered in larger systems are avoided due to the characteristics of diesel generators, there is less room for “just trying things out” as even comparatively small single VRE installations can already have a significant system impact. The primary challenge for small isolated power systems is the fact that technical requirements that are common in transmission level grid codes need to be imposed on relatively small generators connected to medium or low voltage level:

- Low voltage ride-through requirements with dynamic reactive support are crucial for all generators in small systems with low dynamic stability, especially as systems in tropical areas frequently experience short circuits due to difficulties in undergrowth management and severe weather;
- Controllability of all generation units, preferably by remote and in real time, is uncommon in distribution connected generators in larger systems, but important for similarly sized generators in small isolated systems:
- Participation of VRE in frequency control is slowly becoming more common at transmission level in larger systems, but can become important very quickly at much smaller installation sizes in isolated systems (example in Figure 1).

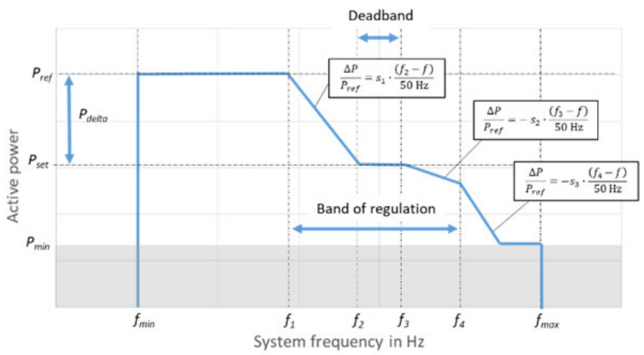

Figure 1: Generic frequency sensitivity requirement for VRE in isolated power systems, based on requirement for larger wind power plants from the Danish grid code.

All these requirements are also necessary when implementing the “all-out” approach with EMS, batteries and potentially even grid forming inverters to allow 100 % non-synchronous penetration at times. For simple VRE integration into otherwise untouched diesel-based systems, choosing requirements wisely can however allow for an increase in VRE capacity and defer investments in batteries and advanced control systems. As mentioned, this can be desirable especially in cases where the system operator has no previous experience with VRE whatsoever. It should be noted that with the continuous reductions in battery prices, driven by the E-mobility sector, the situation may change quickly, and diesel-VRE-battery hybrids with grid forming inverters could become an established starting point more quickly than currently expected. As conference papers tend to exhibit some online longevity, the reader is well advised to note that this paper represents the state of October 2020. In any case, grid forming inverters are currently established technology for systems with a single large inverter, most often the one of the BESS, taking over all system services when in operation. Operation with multiple smaller such units is still uncommon, and larger island systems in the multi-megawatt range may still encounter the same problems a few years from today.

Technical requirements for generators in isolated power systems can be imposed in different alternative ways:

- As requirements in the tender and subsequent agreement in the power purchase agreement (PPA) for installations owned and operated by independent power producers (IPP);
- According to internal guidelines in the procurement and development process, or as project-specific requirements to the engineering-procurement-construction (EPC) contractor, for utility-owned installations;
- In a grid code applicable either only to IPPs or to all generators in a system.

Most currently operational VRE installations in isolated systems have had the technical requirements imposed on a project-specific basis during the tendering process. This has obviously been proven to be successful. The use of suitable equipment is directly agreed on with the EPC contractor and requirements can be fine-tuned to the specific system the generating facility is connected to. However, this approach can be problematic especially for operators of larger isolated systems and operators in charge of a high number of small systems. These may see high numbers of VRE installations if the market conditions and/or incentives are right, and may strive to eliminate excess overhead cost by applying technical rules of at least some uniformity. This exact problem led to the development of grid codes for larger systems, and the same can be done for smaller isolated systems.

VI. Grid Code Development Strategies

As shown, isolated power systems have some unique characteristics by their very nature, but even these can vary quite widely between different systems. It is not too difficult to develop technical requirements that are perfectly suitable to an individual system, but it can be a challenge to develop requirements that are suitable, but do not differ too drastically from those found in larger systems. The latter is important because highly individualized requirements can incur significant additional equipment and development cost. Grid code requirements are a key driver behind the development of new technology features especially in VRE and BESS technology, but development efforts are only undertaken by the manufacturers if there is a significant market for the new features. Small island nations and in a wider sense developing countries usually do not (yet) have large markets that can single handedly drive development. Requirements that cannot be fulfilled without major modifications by equipment that is already state of the art in larger markets will thus result in the need for customized solutions, which can be significantly more expensive.

There are two basic approaches in resolving this problem:

- Grid code requirements for isolated systems can be based on requirements for larger systems, ensuring commercial availability of suitable equipment while potentially accepting some degree of reduction of power quality and security of supply or a limitation of VRE penetration;
- Operators of isolated power systems can cooperate, develop new requirements and hope that their combined market power will drive development.

The former approach is currently the most prevalent. The limits that have to be accepted when following this strategy become less severe with the worldwide uptake in distributed generation, which results in more stringent requirements for distribution connected generators and the commercial availability of advanced technology even at small scale (colloquially referred to as “smart inverters”). It is thus by no means outdated, and this way of developing requirements for generators in isolated systems can be feasible also in the future. This approach can generally be recommended as a first step, especially for operators with little previous experience.

However, when looking beyond “only” integrating some amount of VRE or VRE and BESS systems into diesel-based systems, the latter approach may be the preferable one. The studies conducted by the authors [5][10][11] and several other studies [12][13][14] and real life pilot projects show that for example an annual PV contribution between 15 and 25 % can be reached in systems with modern flexible diesel gensets and suitable control strategies without or with little support from BESS. Even these still relatively low VRE contribution levels can result in instantaneous non-synchronous penetration levels of 70 % or more, and hence require more than only basic technical requirements for generators are needed. There are numerous examples of isolated power systems in which VRE have to be curtailed more often than not, [12][15][16] even at lower penetration levels, and in most cases, the main reason is their lack of remote controllability and capability to assist in frequency control. The authors’ studies in Indonesia showed that a provision for simple setpoint control via mobile internet in combination with a power-frequency droop can be used to greatly increase the PV absorption potential of a system and reduce curtailment (Figure 2), but both requirements are notably absent in most isolated power systems.

To increase contribution further, increasing amounts of storage will be needed, and at some point the logical and economically optimal choice is to implement a system where the diesel gensets can be switched off at least during times of high PV availability. To allow “diesel-off” generation without synchronous generators connected to the grid (Figure 3), the system will need either alternative means of obtaining inertia, such as flywheel storage, or grid forming inverters, typically on the BESS unit(s). High-VRE isolated systems based on both technologies and have been operational for a number of years, but were typically developed as custom installations. Some manufacturers have started offering serially manufactured grid forming inverter technology lately, but the technical characteristics of these are determined by the manufacturer, and no binding technical requirements for the installation of such units in power systems usually exist.

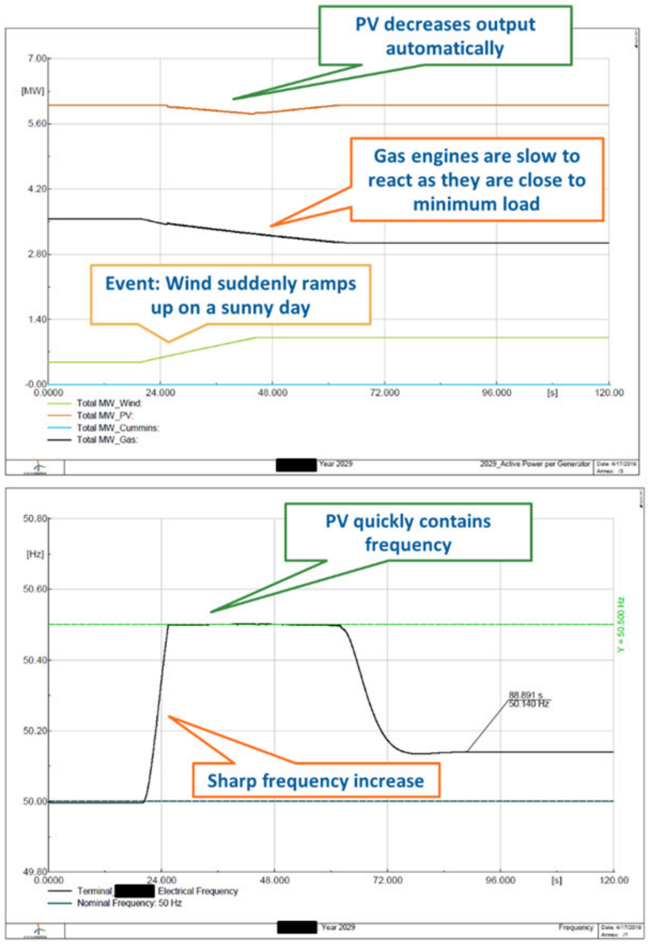

Figure 2: Example from an Indonesian 15 MW system with wind and PV, dynamic RMS simulation in DIgSILENT PowerFactory. PV frequency sensitivity increases VRE penetration potential, as no downward reserve has to be kept on the conventional units.

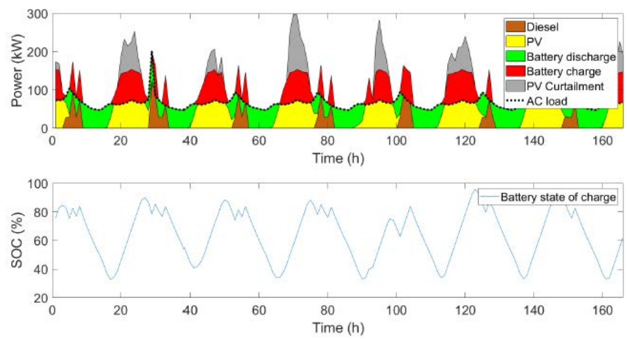

Figure 3: Diesel-off operation in a study case diesel-PV-battery hybrid system in the Caribbean with 100 kW average peak load and 200 kW exceptional peak load.

While the adoption of grid forming inverter requirements into the transmission level grid codes of larger systems is still a controversial and hotly debated issue, [17] there is no question that this technology will become more prevalent very quickly in small power systems where VRE are economically more competitive and which can reach high VRE penetration levels quickly.

VII. Implementation Issues

A. *Ownership structure*

Most large national power systems are either fully unbundled, with grid and generation definitely owned and operated by different parties, or operated as single-buyer systems, with the grid and some of the generators operated by a vertically integrated utility and the rest of the generators operated by IPPs. Island nations such as Barbados and the Seychelles are similarly structured, and their grid codes apply at the boundary between grid operator or utility and the generators. The approach for such systems is hence straightforward, once any issues with suitability of requirements and commercial availability of technology have been addressed. [5][18]

In even smaller systems it is often (but not always) preferred to keep all power system assets under the ownership and governance of the same party, either the utility or a contractor who is in charge of the entire system. For this type of system, the question of whether a grid code is actually necessary is legitimate, as there is no operational boundary between different stakeholders. However, in the majority of cases, either the same utility company owns and operates multiple systems, or at least the same power system regulator is in responsible for supervising all isolated power systems in the same country. In these cases, it is definitely advantageous to formulate a clear framework for technical requirements, either for individual generators or for entire isolated systems. [18]

One such example can be found in the Philippines, where smaller systems outside of the national grid of Luzon, Visayas and Mindanao are operated by a variety of different small utilities. The Philippine Energy Regulatory Commission, by way of their distribution code committee, have implemented the Small Grid Guideline [9], which imposes binding rules both on the utilities and generating companies active in such systems. The guideline, published in 2013, is somewhat out of date and does not reflect the current state of the art especially concerning VRE, but the structure is a very good starting point. As mentioned in the previous sections, the presence of such binding national (or even international) technical frameworks for small systems can reduce development cost for the individual system through economics of scale, and facilitate a large-scale rollout of VRE in isolated power systems.

A stark contrast can be found in Indonesia, where more than 600 isolated power systems are owned and operated by the same party, state utility PLN, but no clear rules exist at all. [1] [2][3] VRE integration has however recently been taking into consideration by PLN, and one major milestone on the way towards that will be a revision grid codes and the development of a technical framework for isolated power systems outside the main grids of Java-Bali, Sumatra, Kalimantan and Sulawesi. This recommendation has been presented to PLN by the authors of this paper within their work in Indonesia as commissioned by the German International Cooperation GIZ GmbH under their REEP – Renenewable Energy for Electrification Programme, suitable regulation is currently under development.

One grid code for multiple systems

As previously mentioned, isolated power systems come in various sizes with different characteristics, and it can be challenging or even impossible to develop uniform requirements that can be applied in all systems subject to the same utility or regulator. For example, Indonesian isolated systems (outside of the main grids, which are also synchronously independent, but in the gigawatt range) range from small village systems supplying a peak load of a few kW in remote areas of Papua and Kalimantan, across megawatt scale systems all around the country, to the larger islands like Belitung (ca. 50 MW) or Bangka (ca. 250 MW). 1 Conditions in the Philippines, Guyana and other South American, African and Southeast Asian are similar, albeit with a smaller number of systems.

In this situation, a nationwide or utility wide grid code for isolated power systems must necessarily be a framework for technical requirements, but leave room in the individual stipulations to take into account local conditions. A similar situation, albeit with much larger power systems, can be found in the EU and the European Commission's efforts to harmonize European grid codes in the EU Network Codes. [19] The Requirements for Generators (RfG) [20] as part of the EU Network Codes have been designed with the following strategy:

- Define generator categories by installed capacity and connection voltage level;
- Set the thresholds between the different categories based on size and characteristics of the individual synchronous area (Figure 4);
- Define which specific requirements must be imposed on generators of each category;
- Leave the exact parameters of the requirements, such as frequency and voltage ranges and LVRT levels ad times to the responsible power system operators;
- Provide guidelines or parameter ranges for each synchronous area.

Synchronous areas	Limit for maximum capacity threshold from which a power-generating module is of type B	Limit for maximum capacity threshold from which a power-generating module is of type C	Limit for maximum capacity threshold from which a power-generating module is of type D
Continental Europe	1 MW	50 MW	75 MW
Great Britain	1 MW	50 MW	75 MW
Nordic	1,5 MW	10 MW	30 MW
Ireland and Northern Ireland	0,1 MW	5 MW	10 MW
Baltic	0,5 MW	10 MW	15 MW

Figure 4: Generator classification as found in the EU Network Code Requirements for Generators (RfG).

This approach can be feasible for isolated systems under the governance of the same party and has recently been recommended to Indonesian state utility PLN by the authors. With the high number of systems present there, a deviation from the EU Network Codes is necessary, as it will not be feasible to work out detailed specifications for each systems.

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[1] Recommendations in this paper are focused on systems between 1 and 100 MW. Indonesia is considering applying transmission code requirements to generators in systems with a peak load exceeding 100 MW, and exempting systems below 1 MW from all requirements.

Isolated systems will hence be categorized as well, with generators categorized for each individual system category. The Philippine Small Grid Guideline follows a very similar approach, classifying grids into five categories and setting requirements for each of them.

Some degree of effort in determining suitable parameters is still required by local utility branches under this approach. The applicability of a binding general framework however increases security for potential investors, IPPs or EPCs to be hired by the utility, and facilitates communication as well as procurement and/or development of suitable equipment.

B. *International harmonization*

The presented approach for the harmonization of rules applicable to multiple isolated power systems under common governance can also be applied to the harmonization of international rules, especially as it has been inspired by an international harmonization framework, the EU Network Codes. [19] This can be of interest especially for system operators of island nations. As explained in section VI, individual small grid operators have virtually no market power to drive new development. This power can be increased by coordinating with other system operators in the region to develop a multinational framework for grid code requirements. Especially the Caribbean and Micronesia have a relatively high density of island nations with individual system operators which would be well advised to coordinate amongst each other. Knowledge sharing is a key component of successful VRE integration and transformation of systems anyways and can yield additional benefits as described if formalized in this manner. [18]

VIII. Conclusion and Outlook

Development and enforcement of technical requirements for generators in isolated power systems are challenging for operators of such systems, especially in developing countries where little previous experience with VRE exists and utilities operate under constrained budgets. Especially the constrained budgets should be considered to be a major driver for mastering the challenge, as VRE can generate at much lower cost than the diesel generators prevalent in isolated power systems.

System operators need to carefully develop requirements and enforcement mechanisms that suit the systems under consideration without becoming so stringent that they present a technical or economical barrier to VRE rollout. Considering the facts that many utilities operate multiple island systems, and that there are many island nations in the world, the best way forward is to exchange experience and develop national or regional isolated power system grid code frameworks. This decreases the burden on the individual operator or operational branch of a utility, and makes it easier and more cost efficient for manufacturers to develop proper equipment.

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