**Digital Protection of Power System**
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**Lecture - 34**
**Introduction to Phasor Measurement Unit – III**

Hello friends, so in the previous lecture we have discussed regarding the hierarchy of Phasor Measurement Systems and then we have discussed the function of data storage devices and use of phasor data for Phasor Measurement Units and we have also discussed about the function of phasor data concentrators and super phasor data concentrators.

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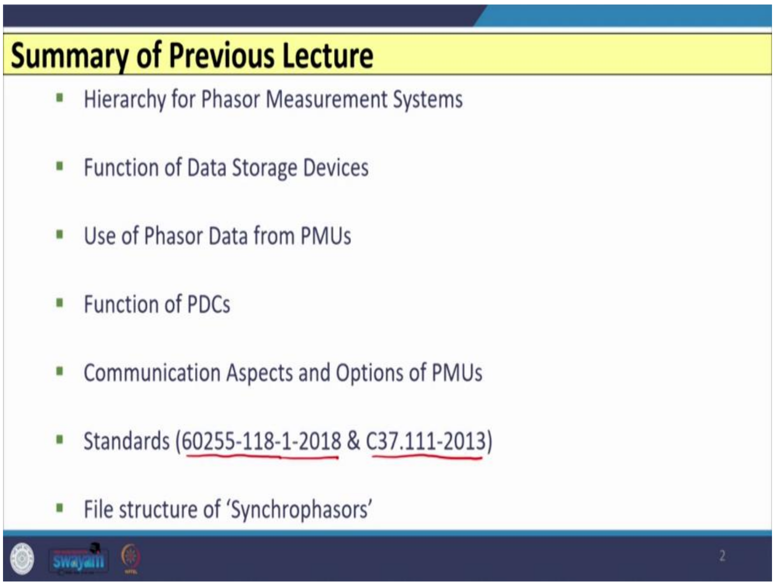


After that, we started discussion with the communication aspects and options available for Phasor Measurement Units and based on this, we have discussed that basically 2 standards are available. The first standard is 60255-118-1-2018, and the second standard is C37.111 which was given in 2013 and at last we have discussed regarding the file structure of Synchrophasors.

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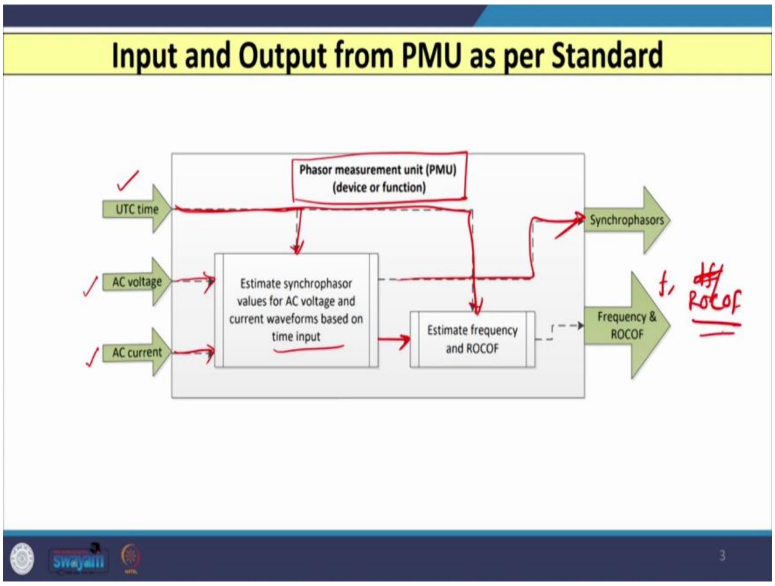


So, with this background, now let us see, what is the input and output block diagram that is available with reference to the PMU as per the standards. So, if I consider that this as our phasor measurement unit which we are discussing, then the input given to this Phasor Measurement Units that is in terms of AC currents, AC voltages, usually bus voltages and AC currents are usually feeder currents or all the feeders connected to the substation.

And the third that is from the universal time clock signal. So, with this 3 signals the inside algorithm of PMU as we have discussed the block diagram of generic PMU. So, phasor estimation of this signals that is voltage and currents that is to be carried out based on the time input. So, the time signal is also given for time stamping and output of this that is given in terms of the phasor values that is what we are interested and that is the output of PMU. Sometimes, if the special estimates are required like the frequency or rate of change of frequency, then that block is also available here which will give you the frequency f as well as the rate of change of frequency that is ROCOF. So, these 2 estimates are also available.

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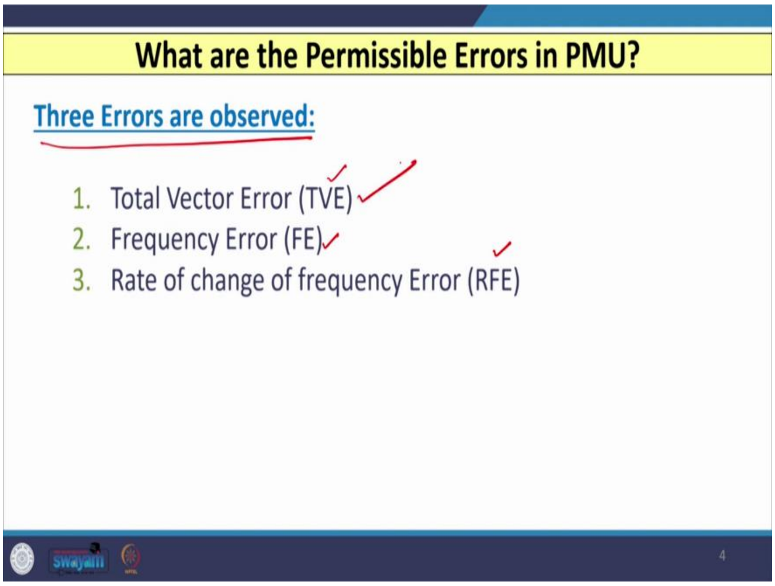


Now, we know that whenever Phasor Measurement Units are used as a device and when we give input as let us say voltage, currents, and the time signal or from GPS or clock signal from GPS, then the output which is estimated by PMUs, they also contain some errors and some reference values are there and if we compare the estimated value with the reference value, then we definitely observed some errors. So, let us see what are the permissible errors as per standards that is permitted in PMU and what are the different types of error that is observed in PMU?

So, normally three errors are observed in PMU and these errors are known as Total Vector Error. normally denoted by TVE. The second is the Frequency Error denoted by FE. and the third is the Rate of change of frequency Error denoted by RFE. So, we will discuss each of this error one by one. So, let us start our discussion with the Total Vector Error denoted by TVE.

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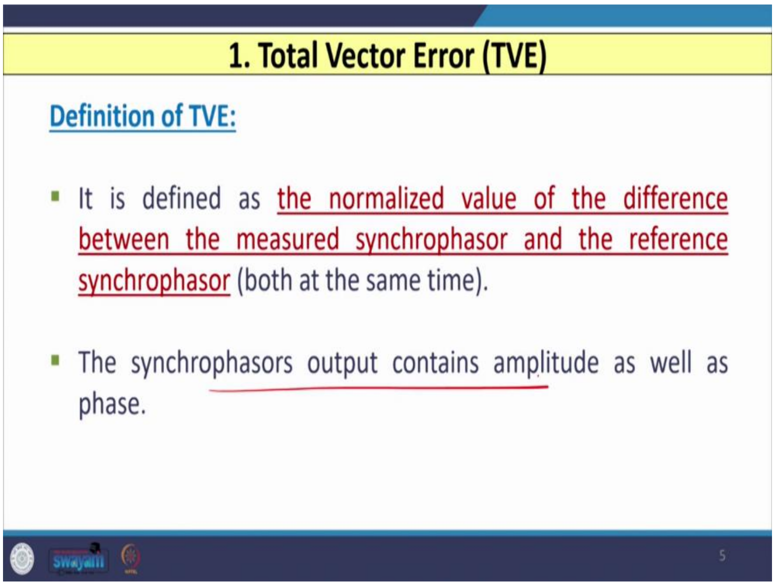


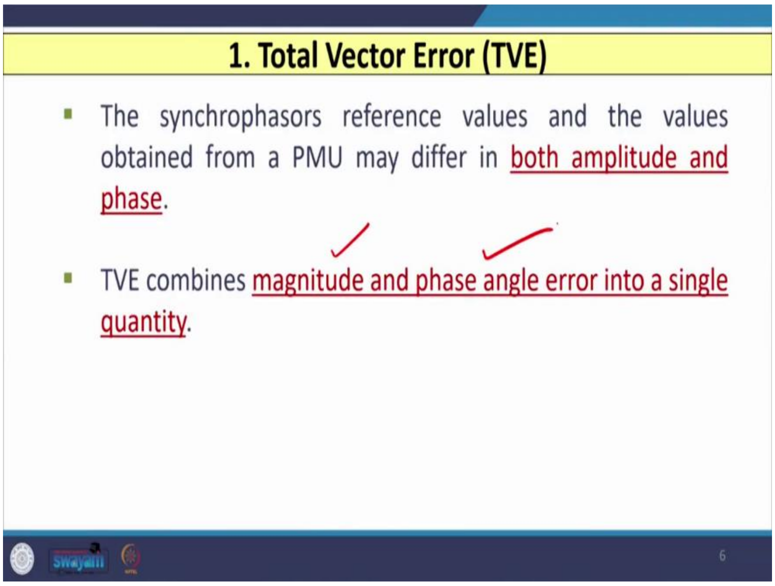


So, how do we define Total Vector Error? So, Total Vector Error is defined as the normalized value of the difference between the measured Synchrophasor that is estimated by the PMU and the reference Synchrophasor that is one reference is there and these 2 are at the same time.

So, normally we know that Synchrophasor output contains both amplitude as well as phase. So, the Synchrophasors reference values and the whatever values obtained or estimated by PMU they may differ both in amplitude as well as in phase. So, Total Vector Error combines both magnitude as well as phase angle error into a single quantity.

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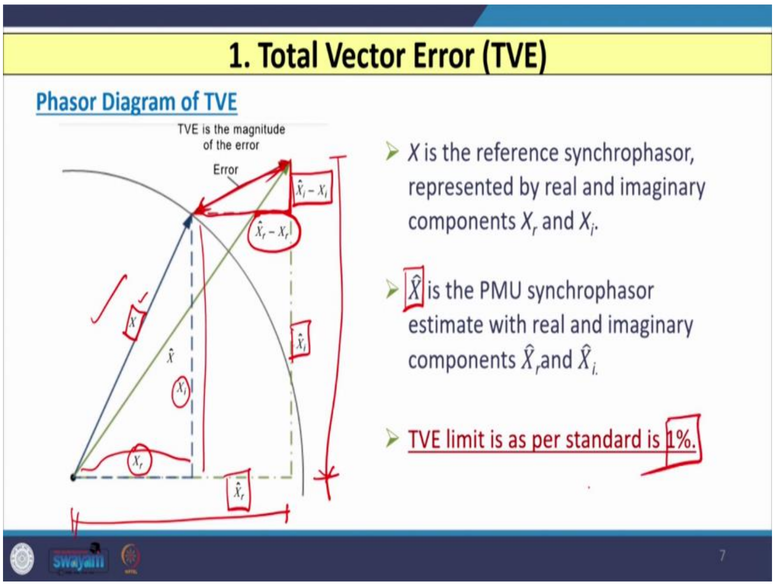


So, if we understand the Total Vector Error with reference to the phasor diagram, then you can see that I have shown one phasor diagram here, (as shown in above slide where this X is nothing but the reference Synchrophasor that is represented by real and imaginary parts. So, its real part is this much that is $X_r$ and its imaginary part that is $X_i$ that is this value. So, this is the reference value, then the other values that is the nothing but the estimated value which is given by the PMU.

So, that value is denoted by the number or symbol that is known as $\hat{X}$, so $\hat{X}$ is the PMU Synchrophasor estimate and if we consider the real part of $\hat{X}$, so that is $\hat{X}_r$ , that is this much and if we consider the imaginary part of $\hat{X}$, so that is $\hat{X}_{i.}$ that is this value so you have this value. So, if you take the difference of this $\hat{X}_r$ and $X_r$, then you will get the error in magnitude part that is real part. And if you take the difference of the $\hat{X}_i$ and the second is the imaginary part of this X that is $X_i$, so $\hat{X}_i$ and $X_i$, then you will get the error part in the imaginary term.

And finally, you will get this error in real part, you will get the error in imaginary part, that is this value that is $\hat{X}_r$ - $X_r$ and that is real part error and the other is the error in imaginary part that is $\hat{X}_i$ - $X_i$, and if you combine this you will have the error which is known as Total Vector Error. And the limit of this Total Vector Error as per the standards that is 1 percent.

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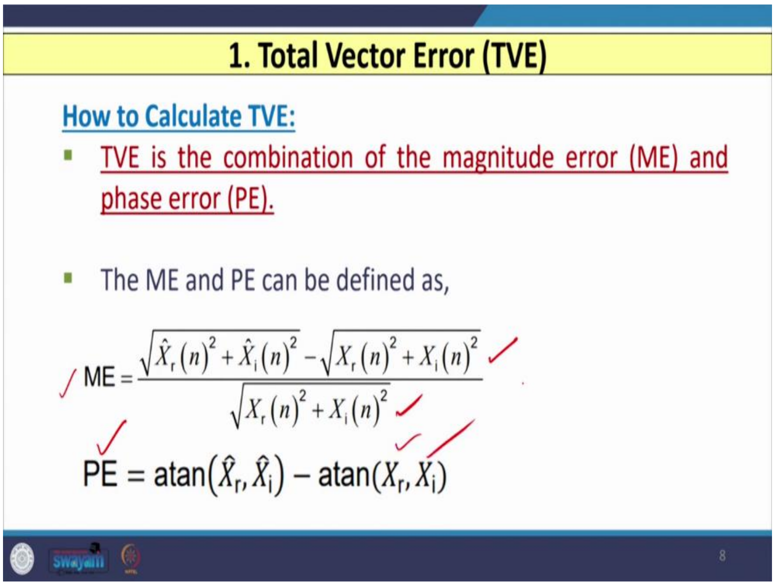


So, now let us see, how we can calculate the Total Vector Error? So, Total Vector Error as I told you it is a combination of both magnitude error and the phase error. So, the magnitude error and phase error that can be defined by these 2 equations,

$$\text{ME} = \frac{\sqrt{\hat{X}_r(n)^2+\hat{X}_i(n)^2}-\sqrt{X_r(n)^2+X_i(n)^2}}{\sqrt{X_r(n)^2+X_i(n)^2}}$$

$$\text{PE} = \text{atan}(\hat{X}_r, \hat{X}_i) - \text{atan}(X_r, X_i)$$

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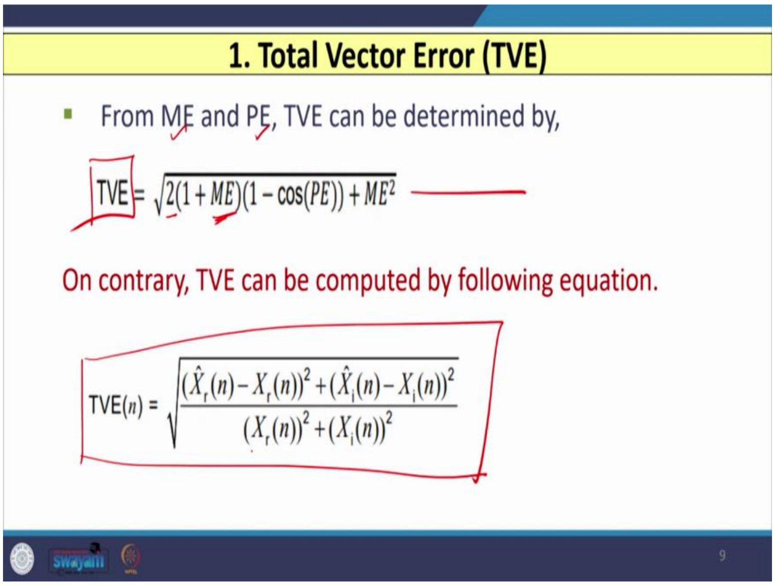

So, once you have the value of magnitude error and phase error then Total Vector Error can be determined by this equation,

$$\text{TVE} = \sqrt{2(1+ME)(1-\cos(PE)) + ME^2}$$

So finally you will have the Total Vector Error. So, this is 1 of the way, that if I wish to calculate the Total Vector Error in PMU then what I do is, I will calculate first magnitude error, then I calculate the phase error and based on this using this equation, we can calculate the value of Total Vector Error.

However, sometimes if you wish to calculate the Total Vector Error without calculating magnitude error and phase error then also you can do and for that you have to use this equation.

$$\text{TVE}(n) = \sqrt{\frac{(\hat{X}_r(n) - X_r(n))^2 + (\hat{X}_i(n) - X_i(n))^2}{(X_r(n))^2 + (X_i(n))^2}}$$

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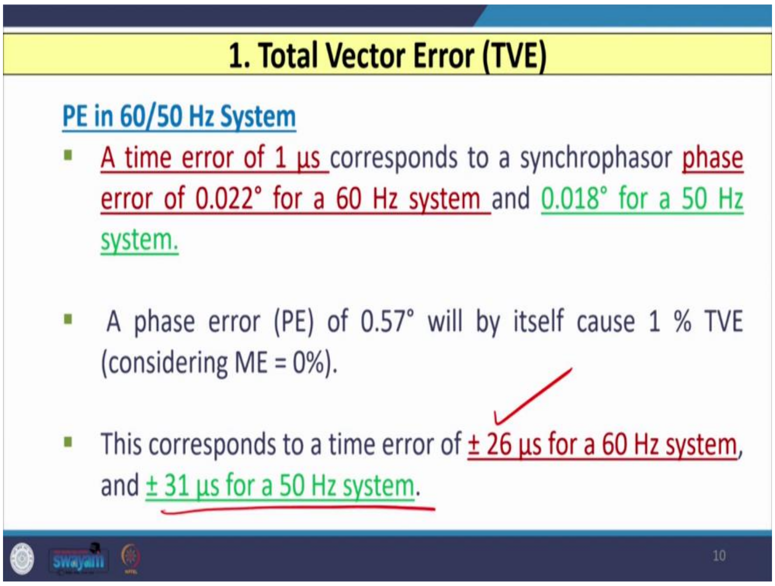


Now, if I consider the phase error for a particular 50 Hz or 60 Hz system, then a time error of 1 micro second that is correspond to the Synchrophasor phase error of 0.022° for a 60 Hz system and 0.018° for a 50 Hz system. So, a phase error of 0.57° that will be itself cause 1 percent Total Vector Error, assuming that magnitude error is 0 percent. So, this will correspond to the time error of plus or minus 26 microsecond for 60 Hz system and 31 micro second for 50 Hz system, so this you can consider in the calculation.

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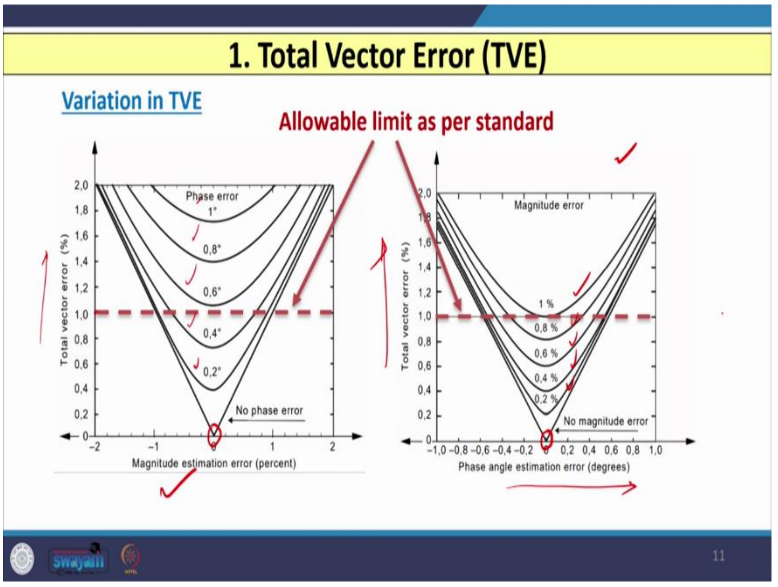


If I just plot the variation in Total Vector Error with reference to the magnitude error and then again with the Total Vector Error with reference to the phase error, then in the first graph, you can see, I have considered the variation between the magnitude error on x-axis in percentage and Total Vector Error on y-axis assuming that my phase error that will be 0, then you will have this curve.

And if you increase the phase error, let us say 0 to 1 degree, then you will have the different curve like this and you can see that this 1 percent of Total Vector Error that is the allowable limit as per standard. Same way, in the second graph also you can see that I have taken the phase error on x-axis in degrees and Total Vector Error in percentage on y-axis and if I consider magnitude error is 0, then you will have this graph, and further if you go on changing this then you will have the variation in this graph, again, the 1 percent Total Vector Error limit is also applicable for this graph.

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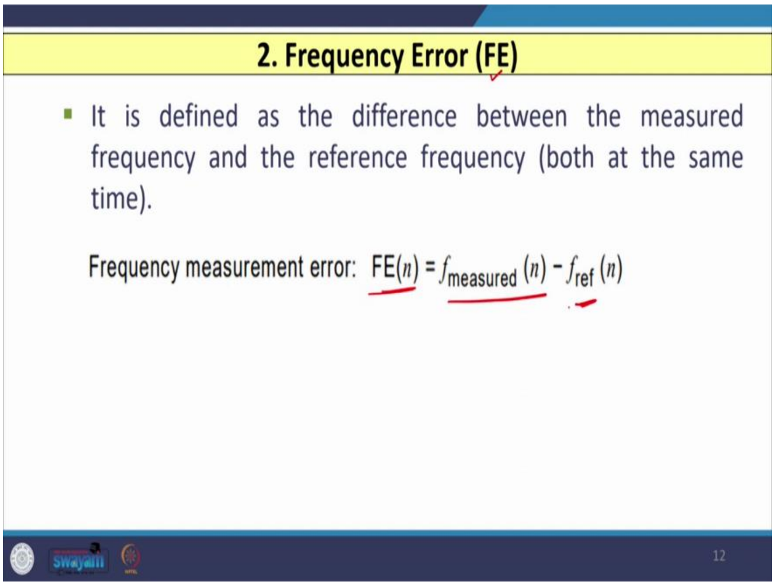


Now, let us see the second type of error that is known as Frequency Error, usually denoted by FE. So, Frequency Error is defined as the difference between the measured frequency, and the reference frequency, both at the same time. So, if I write down mathematically, then

$$\text{Frequency measurement error:} \quad FE(n) = f_{measured}(n) - f_{ref}(n)$$

So, this is how we can represent Frequency Error during the measurement.

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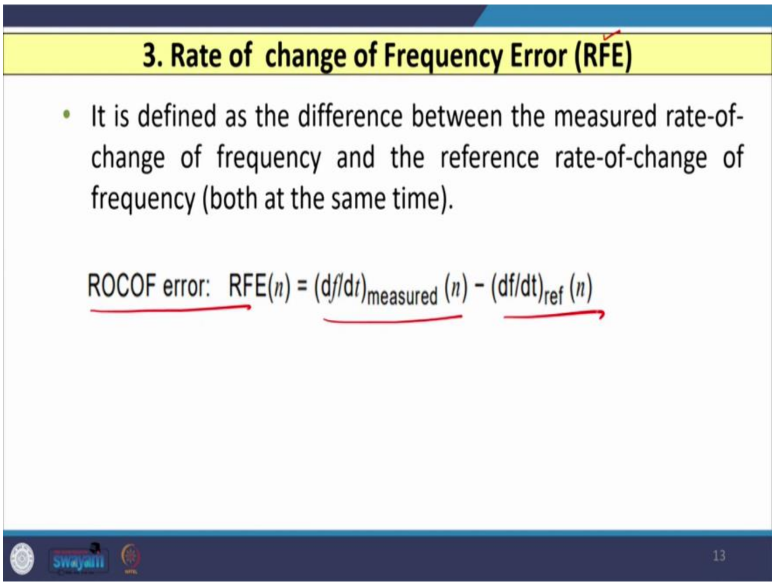


The third thing is the Rate of change of frequency Error normally denoted by RFE. So, Rate of change of frequency Error is defined as the difference between the measured value of rate of change of frequency and the reference value of rate of change of frequency both at the same time. So, mathematically error in ROCOF that is RFE at particular sample number that is given by,

$$\text{ROCOF error:} \quad RFE(n) = (df/dt)_{measured}\,(n) - (df/dt)_{ref}\,(n)$$

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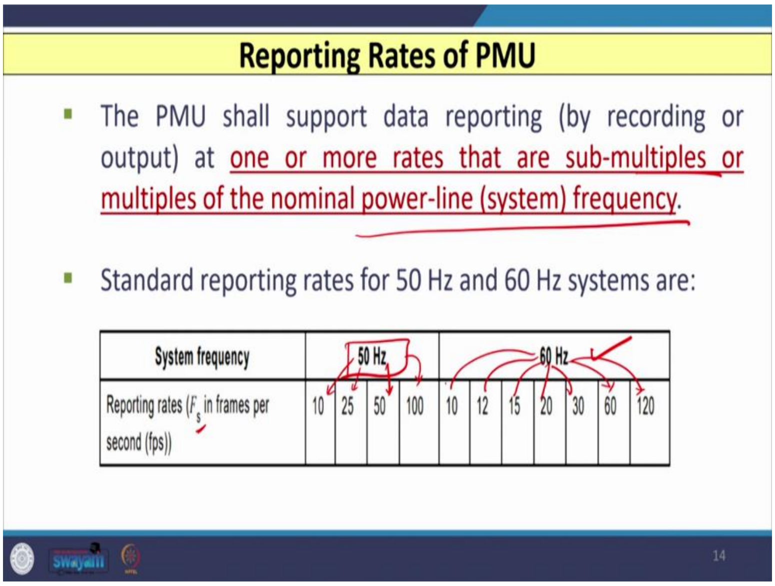


Now, with these errors, if I consider the reporting rates of phasor measurement unit, then all the PMUs shall support data reporting rate this is applicable for both recording as well as output at one or more rates that are either multiples or sub multiples of the fundamental frequency. So, standard reporting rates for 50 Hz and 60 Hz systems are shown in this table, so this is for 50 Hz, and this is for 60 Hz.

So, reporting rates normally denoted by $F_s$ that is in frames per second, so you can see that for 50 Hz (as shown in above slide) the highest reporting rate of PMU is 100 which is multiple of 50 or maybe 50 or maybe sub-multiples of 50 that is 25 and 10. Same way, if you consider 60 Hz, then you will have the highest reporting rate that is 120 and then 60 and then sub-multiple of 60, those are also available here.

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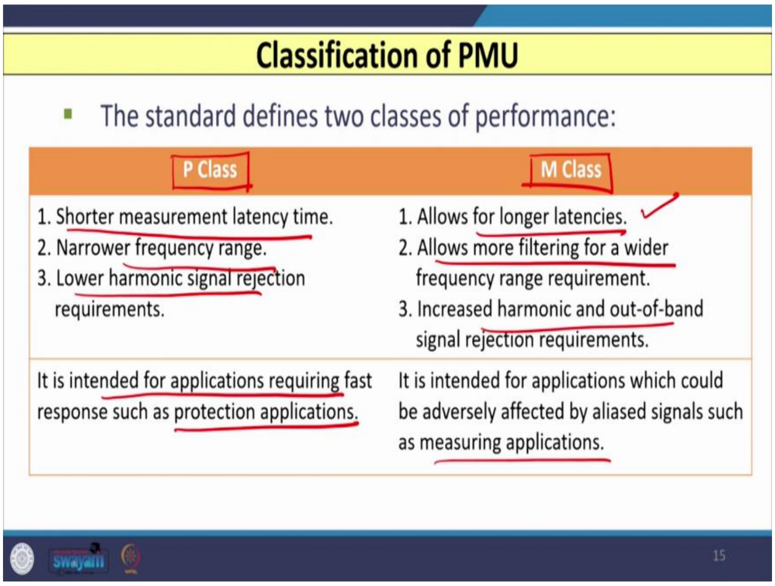


Now, let us see how we can classify phasor measurement unit? So normally, we can classify the Phasor Measurement Units based on its performance and this is classified by 2 ways. One is the P class PMU and the other is the M class PMU. The name P is given because it is used for protection purpose and the M is given because it is used for measurement purpose. So, let us see what is the difference between the P class and M class PMU.

So, if I consider the P class PMU then in this P class PMU, the measurement latency time is shorter compared to the M class PMU, where in case of M class PMU longer latencies are observed, whereas here the shorter latencies that is observed. If I consider the second point, then the frequency range is narrower in P class whereas the M class PMU allows more filtering for a wider frequency requirement.

The third point for P class PMU is the lower harmonic signal rejection requirements are there, whereas in case of M class PMU this requirement that is increased and it is also out of band signal rejection requirements are also there, and because of these 3 important points for P class PMU, this type of PMU is used for the fast response particularly in protection applications. Whereas, as the response of M class PMU is slow because of the higher latencies and the more filtering for a wider frequency range requirement, then this type of PMU is used normally for measuring applications. So, this is the main difference between the P class PMU and the M class PMU.

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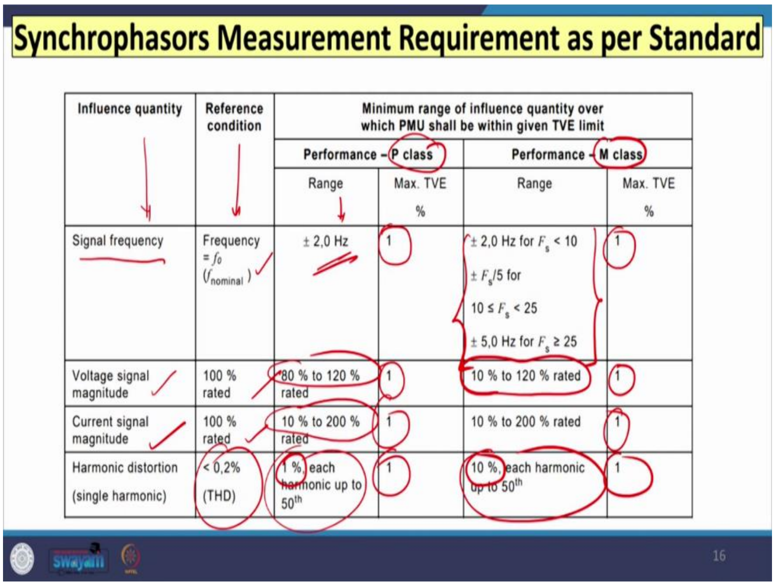


| Influence quantity | Reference condition | Minimum range of influence quantity over which PMU shall be within given TVE limit | | | |
|---|---|---|---|---|---|
| | | Performance – P class | | Performance – M class | |
| | | Range | Max. TVE % | Range | Max. TVE % |
| Signal frequency | Frequency = $f_0$ ($f_{nominal}$) | ± 2,0 Hz | 1 | ± 2,0 Hz for $F_s < 10$<br>± $F_s/5$ for $10 \le F_s < 25$<br>± 5,0 Hz for $F_s \ge 25$ | 1 |
| Voltage signal magnitude | 100 % rated | 80 % to 120 % rated | 1 | 10 % to 120 % rated | 1 |
| Current signal magnitude | 100 % rated | 10 % to 200 % rated | 1 | 10 % to 200 % rated | 1 |
| Harmonic distortion (single harmonic) | < 0,2% (THD) | 1 %, each harmonic up to 50th | 1 | 10 %, each harmonic up to 50th | 1 |

Now, let us see what is the Synchrophasor measurement requirement as per the standard? So, here I have shown one table, where you can see the quantity which is influenced I have shown and the reference condition for that particular quantity is also mentioned and for both P class PMU, and M class PMU, the performance is given in terms of the Total Vector Error, that is maximum allowable Total Vector Error and the range of frequency. So, for particular range of frequency how much maximum Total Vector Error in percentage is allowed for P class PMU and same is for M class PMU.

So, if we consider the signal frequency then and if I consider the nominal frequency, then you can see (as shown in above slide) that for P class PMU, again the Total Vector Error is 1 percent and for M class also it is 1 percent, but you see the difference that the range of frequencies here, that is plus or minus 2 Hz, whereas in case of M class PMU, the wider range of frequency that is available for same 1 percent allowable Total Vector Error.

If I consider the second point voltage signal magnitude then 100 percent is the rated value or nominal value, then the range is allowed for 1 percent Total Vector Error for P class PMU is between 80 to 120 percent of the rated value. So, again the wider range of change in voltage that is available for measurement class PMU for same value of Total Vector Error in percentage.

If I consider the current signal with the rated value, then again, the 10 to 200 percent of the rated value that is available, that range is available for same 1 percent TVE and similarly, for M class PMU, the same value that is 10 to 200 percent that is there, so both are same. Harmonic distortion, if I consider then for same P and M class PMU for same percentage of TVE 1 percent, you can see that the THD, that is the harmonic distortion allowed, that range you can see that is totally different.

Here, 1 percent, each harmonic up to 50th that is the range of P class PMU, whereas for measurement class PMU, it is 10 percent for each harmonic up to 50th harmonic. So, here 1 percent, whereas here 10 percent for each harmonic up to 50th, so that is the main change or difference between the performance of P class and M class PMU.

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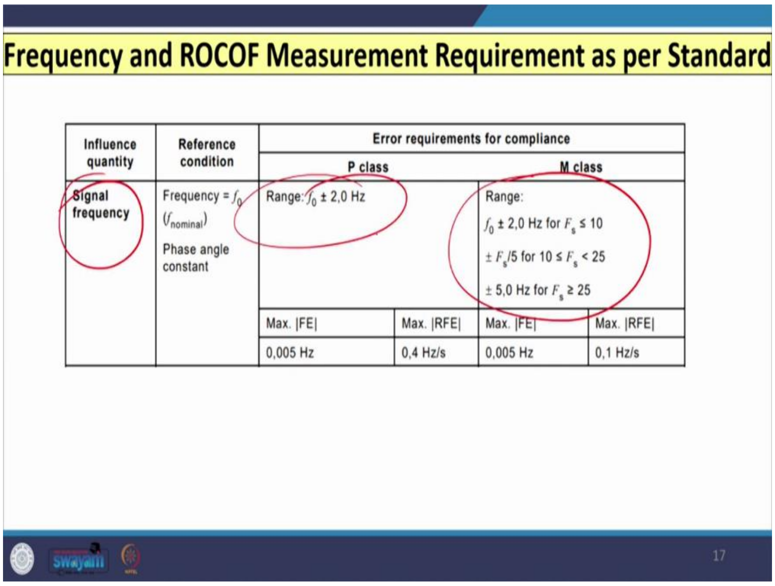


Same way, you can also see that wider range is available in M class PMU, so this is just a comparison that what wider range is available in M class PMU for same Total Vector Error that is 1 percent allowable compared to the P class PMU.

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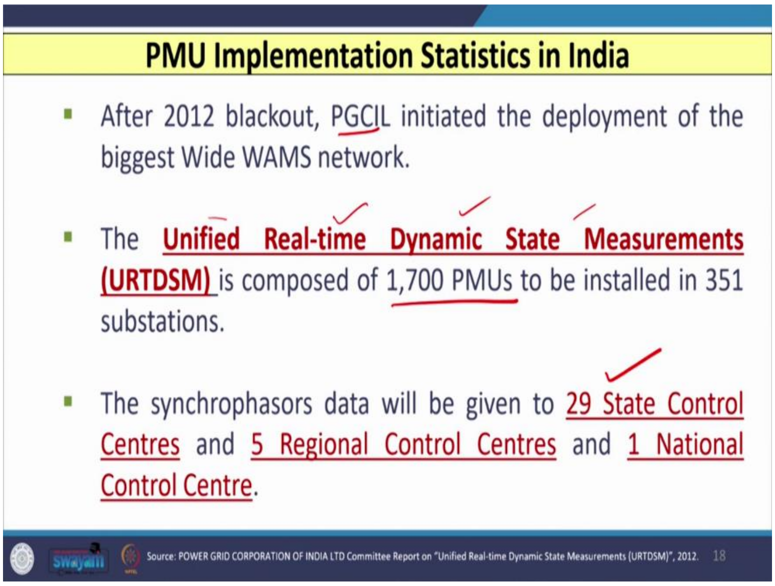

Now, let us see what is the statistics of the implementation of PMUs in India. So, after 2012 blackout, Power Grid Corporation of India limited, initiated a huge project for the deployment of the WAMS network in different regions of our country. And they have started a scheme that is known as URTDSM, and it is known as Unified Real Time Dynamic State Measurement Scheme, normally, it is denoted by URTDSM, so URT is for Unified Real Time, and DSM is the Dynamic State Measurement.

So, in this scheme, it is proposed to installed 1700 PMUs in different 351 substations across the India, and it is also proposed that the Synchrophasors data that will be available or given to 29 different state control centres, 5 regional control centres, and 1 national control centres. So, this is the main statistics of the PMU implementation in our country as per URTDSM scheme. Now, let us see what are the recommendations, because this URTDSM has also given certain recommendations and suggestions.

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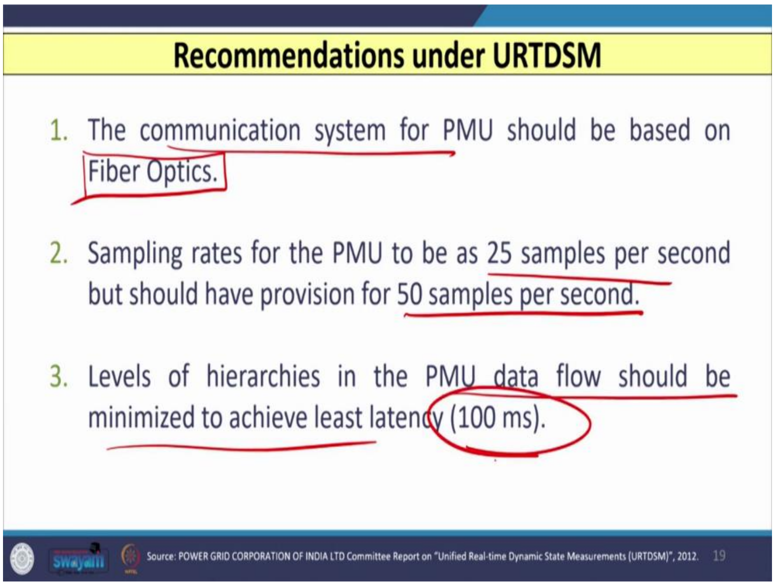


So, these recommendations are the first recommendation is the communication system for PMU that should be based on fiber-optics. The second recommendation is the regarding the sampling rate of PMU and URTDSM has proposed that the sampling rate for the PMU that is to be 25 samples per second but should have a provision of higher, that is 50 samples per second also, so this is also mentioned or recommended by the URTDSM.

The third is related to the hierarchies of PMU and we have already discussed the hierarchies of PMU and we have seen that, normally, upward flow of direction from data storage device to PMU to PDC to super PDC, that is followed. However, in rare case may when some PDC wants data in some specific format then the downward or reverse direction flow is also possible, so this third recommendation of URTDSM is related to the hierarchies of PMU and it is mentioned that PMU data flow should be minimized to achieve the latency of the order of 100 millisecond.

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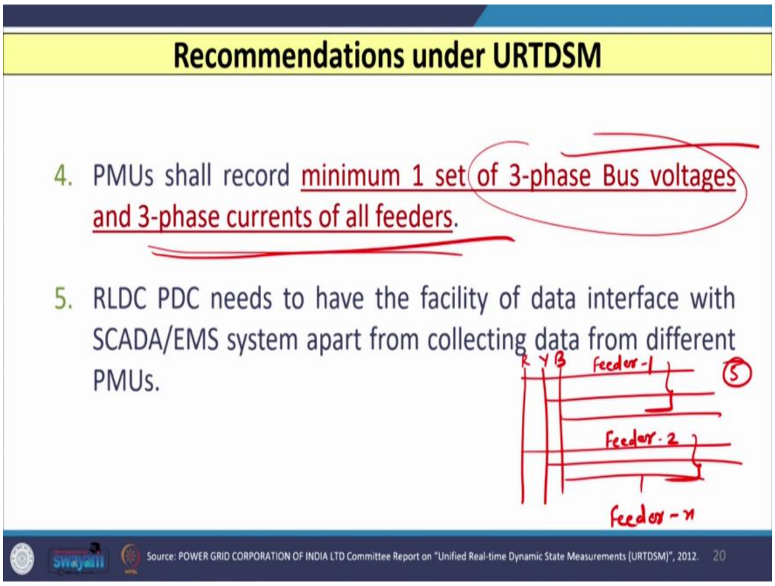


The fourth recommendation that is PMU shall record minimum of one set of 3 phase bus voltage that is there in substations and the 3 phase currents of all the feeders. So, for example, if in the substation, we have the 3 buses, and from these 3 buses let us say this is R Y B, so all the 3 voltages that is one set of 3 phase bus voltages that has to be measured by or record by PMU. And if number of feeders are emanating from this, let us say, this is 1 feeder, the another feeder is also there, let us say 5 feeders are there, so these 3 phase currents of all the feeders that should be recorded by PMU that is the meaning of this.

So, this is our feeder 1 which contains 3 currents, similarly we have the feeder 2 that also contains 3 currents and so on. And then, feeder n, so all this current that should be recorded by PMU. Then the RLDC that is regional load dispatch centre, PDC needs to have the facility of data interface with the conventional supervisory control and data acquisition system or energy management system, apart from collecting the data from different PMU.

So, your whatever PDC you have installed at regional load dispatch centre, this PDC is capable to collect the data from different PMUs, those are connected with that PDC. Along with that it is also capable to interact with the conventional SCADA or energy management system. So, this is also suggested or recommended by URTDSM.

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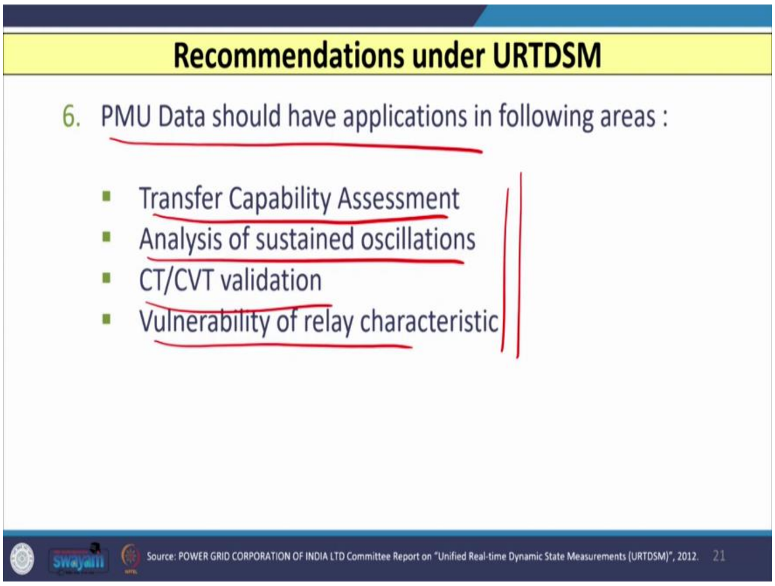


And the sixth recommendation of URTDSM is regarding the PMU data, how we can use the PMU data for what applications? So, they have suggested the 4 major applications, the first one is related to the transfer capability assessment, the second is the analysis of sustained oscillations if it is there in the system, the third is related to the validation of current transformer or capacity voltage transformer, and fourth that is related to the vulnerability of relay characteristics. So, if any swing or that is available or inserted in particular zone of the relay characteristic then that is also monitored by this.

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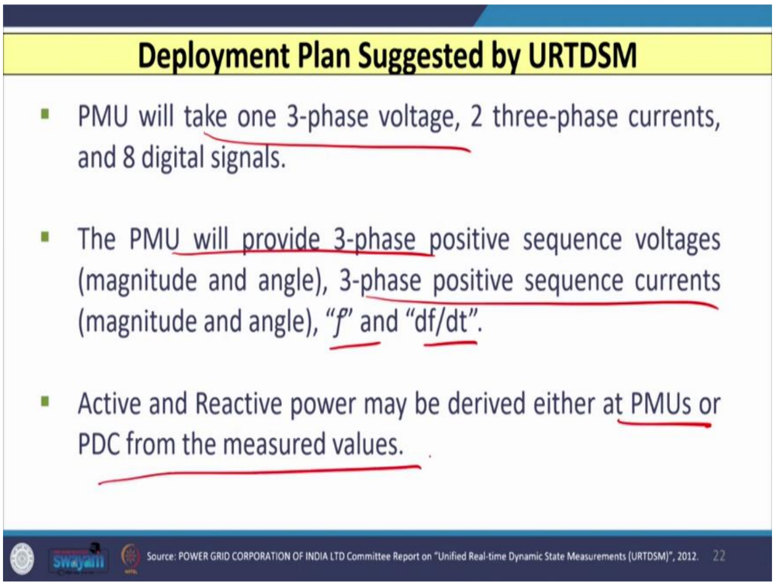


Now, based on this deployment that is suggested by URTDSM in our country they have also suggested some plan. So, PMU will take care of one 3 phase bus voltages and feeder currents and 8 digital signals. The PMU will provide 3 phase positive sequence voltages, 3 phase positive sequence current, so voltage and current estimates are there, phasor values of voltage and current. Along with that, if required, they can also give the frequency and rate of change of frequency. Active and reactive power may be delivered either at PMU or PDC from the measured value, so this is also one of the requirements.

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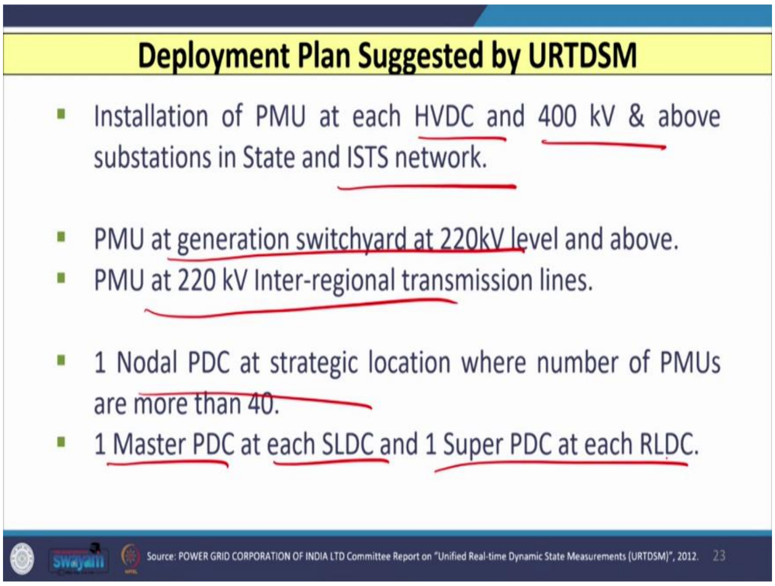


Installation of PMU at each HVDC and 400 kV and above substations in state and interstate transmission system network that is also suggested by this URTDSM. PMU at generation switch yard at 220 kV level and above that is also suggested, PMU at 220 kV inter regional transmission lines that is also suggested. One nodal PDC, that is required at strategic location, where the number of PMUs are more than 40, so that is monitored by this PDC. One master phasor data concentrator each at a state level dispatch centre, and one super PDC at regional load dispatch centre, that is also required.

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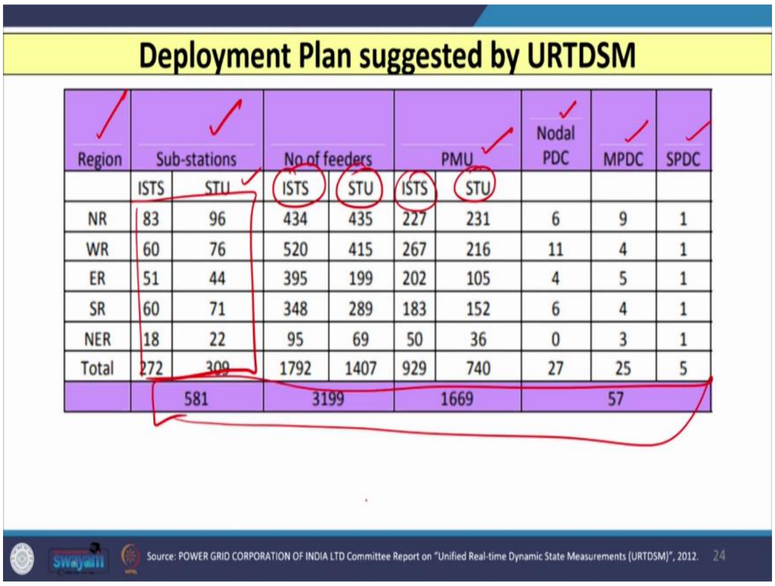


| Region | Sub-stations | | No of feeders | | PMU | | Nodal PDC | MPDC | SPDC |
|---|---|---|---|---|---|---|---|---|---|
| | ISTS | STU | ISTS | STU | ISTS | STU | | | |
| NR | 83 | 96 | 434 | 435 | 227 | 231 | 6 | 9 | 1 |
| WR | 60 | 76 | 520 | 415 | 267 | 216 | 11 | 4 | 1 |
| ER | 51 | 44 | 395 | 199 | 202 | 105 | 4 | 5 | 1 |
| SR | 60 | 71 | 348 | 289 | 183 | 152 | 6 | 4 | 1 |
| NER | 18 | 22 | 95 | 69 | 50 | 36 | 0 | 3 | 1 |
| Total | 272 | 309 | 1792 | 1407 | 929 | 740 | 27 | 25 | 5 |
| | 581 | | 3199 | | 1669 | | 57 | | |

So, if I just understand the deployment plant as suggested by URTDSM, then you can see (as shown in above slide) that I have given the regions starting from northern, western, eastern, southern, and north eastern regions, and then in second column, I have mentioned the substations, where I have the inter-state transmission systems, and state transmission utilities are also there, the values are there so this is also mentioned.

Number of feeders are also mentioned for this ISTS and STU and for each ISTS and STU how many PMUs are required northern region, western region, so region wise that is also given in this column. And then, for this PMUs, how many PDCs are required, nodal particularly who is going to monitor that, and above this nodal you have the MPDC and SPDC, all these things are given and total PMUs are also mentioned in the last row. So, this is all about these deployment plan as suggested by the URTDSM.

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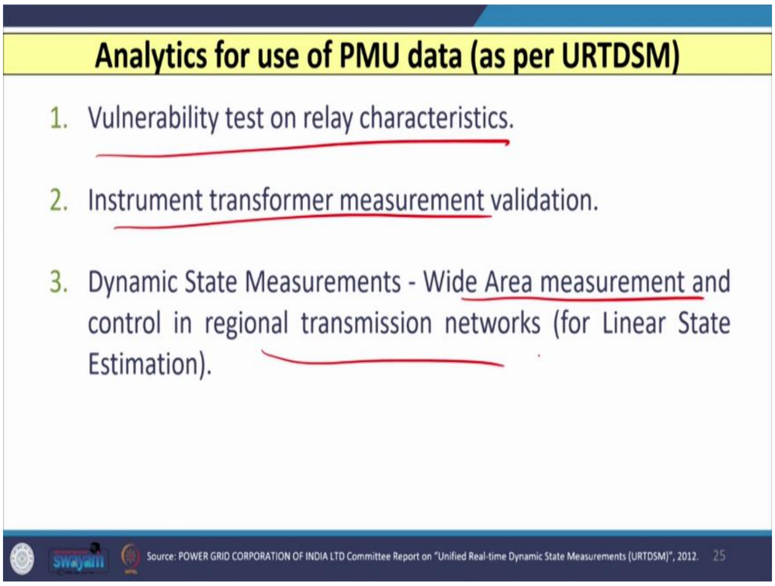


Now, let us see what is the analytics for the use of PMU data for what purpose we will use the PMU data. So, we can go for vulnerability test on relay characteristic as I told you, for instrument transformer validation CT on CVT, for dynamic state measurements may be for wide area measurements and control in regional transmission network that also we can use.

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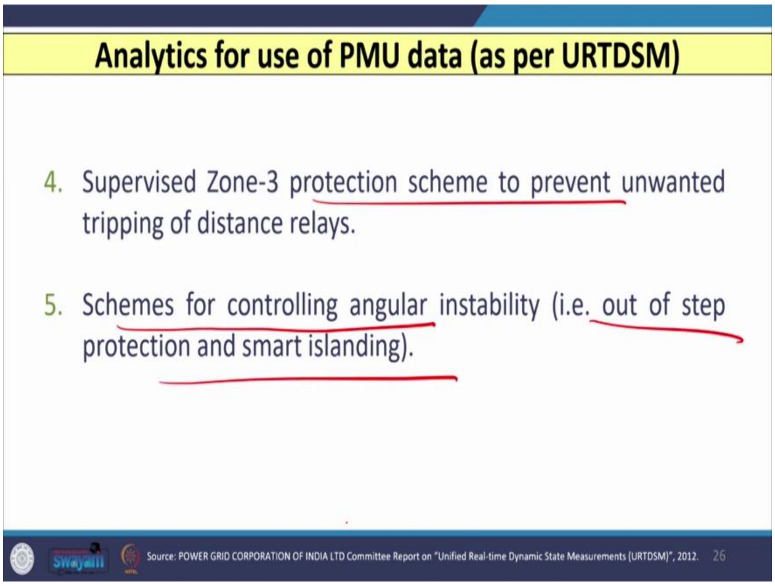


We can also go for the supervision of zone 3 protection scheme to prevent the unwanted operation of distance relays, and because of which the last 2012 blackout happened, and we can also design the schemes for controlling angular instability that is out of step protection and smart islanding if it is there.

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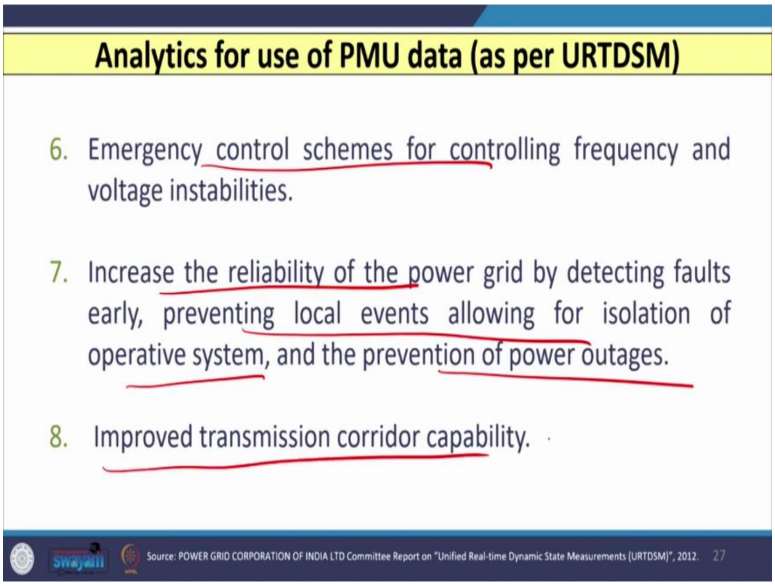


And further, we can also extend the use or utilization of PMU for emergency control schemes for controlling frequency and voltage instabilities. We can also increase the reliability of power grid by detecting the faults at early stage. Preventing the local events, allowing for isolation of operative systems, and maybe for the prevention of power outages. And we can also use the PMU data for improved transmission corridor capability.

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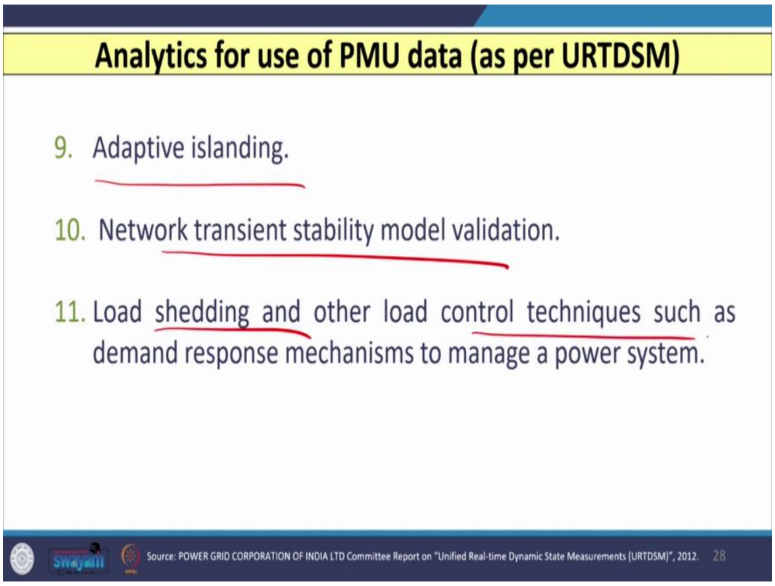


May be, if we wish to achieve the concept of adaptive islanding, that is also fulfilled using PMU data. Network transient stability model validation is also possible and we can also use for load shedding and other load control techniques such as demand response mechanism to manage the power system.

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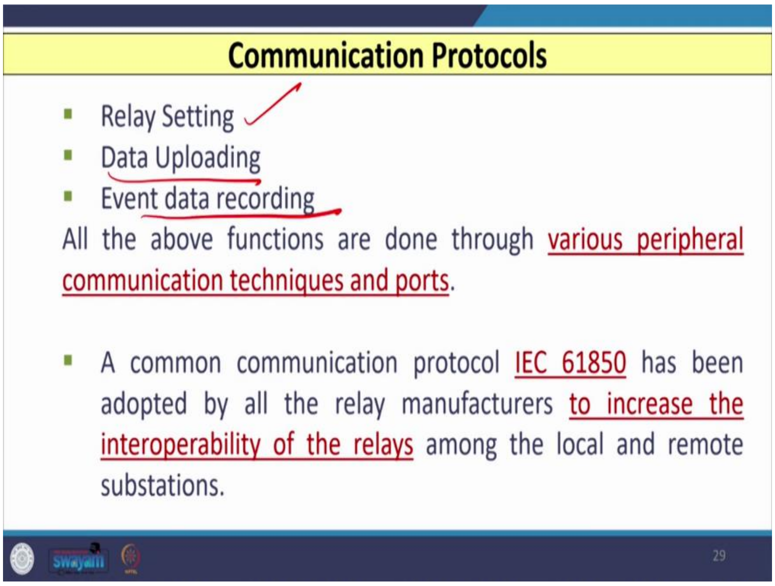


So, this is all about the what is the deployment status and plan and what are the recommendations as suggested by URTDSM. Now, the most important point is the protocols. So, communication protocols play an important role, because whenever we consider the Synchrophasors which contains PMU, PDC, super PDC, then how the communication between 2 PMUs is carried out? How the communication between PMU and PDC or PDC and super PDC that is to be carried out? Those are based on certain communication protocols. So, this includes the Relay Settings, Data Uploading, Event Data Recording, and all these functions are done through various communication techniques and ports based on certain standard protocols.

So, a common communication protocol which is known as IEC 61850, that has been adopted by all the relay manufacturers throughout the world, and this they have accepted because to increase the interoperability among the relays manufactured by different manufacturers. This we will discuss in the next class.

So, in this lecture we started our discussion with the what is the input output flow in the PMU. Then, we have discussed the what are the different errors possible in PMU and we have discussed 3 important errors, one is the Total Vector Error, second is the Frequency Error, and another is the Rate of change of frequency Error. And then, we have also discussed that how we can calculate those errors using what equations.

And at last, we have discussed the what is the implementation statistics of PMUs in our country and based on URTDSM they have suggested certain recommendations that also we have discussed. And finally, we have discussed the communication protocols because ultimately all depends on how one PMU will communicate with other PMU or PDC, so this is based on certain communication protocols and that protocols is nothing but the IEC 61850 protocols. So, this we will discuss in the next class. Thank you.