Power system security economy availability engineering essay

Engineering

Introductionquality are the main objectives. Last three of which, directlyaffect the customer. But in the recent years due to the rapiddevelopment in the electronics and digital computers the natureof the load has changed from mostly conventional such as motorsand filament bulbs to mostly non-linear loads that use switchmode power supplies (SMPS), electric drives and compactfluorescent lamps (CFL). That unfortunately for the power systemhas made the quality issue more serious. Power quality is anything that affects the voltage, current andfrequency of power being supplied to the customers. Constantvoltage is the prime requirement of the customer because if thevoltage is lower than the tolerable limits it will cause overheating of the equipment and less illuminating power to thelighting load. If it is higher than the limit it cause materialinsulation break down, reduces the life of lighting load etc. Lightning (transient over voltages), switching over voltages (i. ecapacitor switching, disconnection of lines), short circuitfaults (such as voltage sags) and short interruptions are themain causes for voltage deviations which lead to permanent damageof the equipment. Power system frequency is related to the balance between powergeneration and the load. When this balance changes, small changein frequency occurs. The frequency variations that go beyondacceptable limits for normal steady state operation of powersystem are normally caused by fault on the transmission lines, large portion of load being disconnected, or a large source ofgeneration being isolated. Drop in frequency could result highmagnetizing currents in induction motors and transformers, causing problem of overheating and saturation. Off nominalfrequency will cause damage to turbine and generator due to highvibration of turbine blades which causes protection to trip out. Therefore it is essential requirement to maintain frequency ofthe system within the tolerable limits. Nowadays due to lot of harmonic injection in to the power systemby the load that are also more sensitive in nature, the use ofcustom power devices/custom controllers (electronics based) tomaintain power quality has become essential. As custom powercontrollers are used for current interruptions and voltageregulations, their utilization in the industry saves itsequipment from voltage dips and interruptions which lead to lossof production. Minimize total harmonic distortion (THD) andimprove the load power factor that minimizes the losses in thenetwork. This chapter will present an overview of major power qualityissues at the distribution level: voltage disturbances, harmonics, transients, unbalance and flickers. Moreover differentsolutions for mitigation of these issues by using custom powerdevices along with some case studies will also be presented. 1. 1 Power quality IssuesPower quality issues occur due to different type of electricaldisturbances that depends on amplitude and/or frequency. Thesedisturbances are divided into short, medium or long termdepending upon their duration. The power quality disturbancesthat most often occur at the distribution level are discussedbelow. 1. 1. 1 Voltage DisturbancesVoltage disturbances are characterized by their duration anddepth. Duration is the length of time for which the voltageremains below a threshold. The depth is characterized by theretained voltage, which is the voltage that persists during thevoltage disturbance, as opposed to the voltage decrease. IEEE definition of voltage sag is described as a sudden and shortduration reduction in RMS value of the voltage at the point ofelectrical system between 0. 1 to 0. 9 pu with duration from 0. 5cycles to 1 minute. It is known as a voltage swell if there is an increase between1. 1 pu and 1. 8 pu in RMS voltage at the power frequency fordurations from 0. 5 cycles to 1 minute. In case, the voltage is completely lost or is less than 0. 1 pu inone or more phase conductors for a period between 0. 5 cycles and1 minute than it is known as interruption. Any disturbance that persists for less than 0. 5 cycles isconsidered a transient phenomenon while the one that is longerthan 1 minute could be overvoltage, undervoltage or sustainedinterruptions depending upon the RMS voltage magnitude greaterthan 1. 1 pu, less than 0. 9 pu or completely lost or less than 0. 1pu respectively. These voltage disturbances are categorized inthe Figure [fig: VoltDisturb] with respect to RMS voltage and timeduration of the disturbance. Short duration voltage disturbancesmostly depend upon the location of the fault and also on thecondition of the power system. Figure [VoltDip] and [VoltIntp]show some fault events [1].[float Figure:[Figure 1. 1: Categorization of Voltage disturbances.]

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Voltage sags occur a lot in a power system that’s why they areconsidered the most severe disturbance to industrial equipment. Disturbance of only 10% sag for duration of 100ms can affect thequality of papers in paper mill [3]. In case of semiconductorindustry, voltage sag of 75% (of the nominal voltage) withduration shorter than 100ms results in material loss in the rangeof thousands of U. S dollars [2]. The cause of voltage sag couldbe due to different events in the power system like short circuitfaults in the transmission and distribution system, starting oflarge Induction motor or transformer energizing can also resultin shallow dips [4].[float Figure:[float Figure:[Sub-Figure a:

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[Figure 1. 2:(a) Voltage Dip and (b) Voltage Interruption events.

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[float Figure:[Figure 1. 3: Faults on parallel feeder causing voltage sag]

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In case of three phase voltage sag due to a fault at the point ofcommon coupling (PCC) in a radial system, as shown in Figure [feeder]. The Voltage divider model can be used for the calculation ofvoltage sag magnitude. In this case voltage overline{E}gduringfault can be expressed asoverline{E}_{g}= frac{overline{Z}_{f}}{overline{Z}_{g} +overline{Z}_{f}}*overline{E}_{s}Where overline{Z}_{g}is the impedance of the grid, overline{Z}_{f}is the impedance between the PCC and the fault including faultand line impedances and overline{E}_{s}is the supplyvoltage. Voltage sag is also related to the changes in voltagephase angle. This change in phase angle is also called as phaseangle jump (i. e the phase angle between during sag and pre-sagvoltages) and is obtained by taking argument of the complex ofvoltage Eg [5]. Long duration voltage variations are mostly due to inadequatevoltage regulation, equipment malfunction or failure or switchingof large loads in a power system. Figure [Overvoltage] presentsan overvoltage caused by a transformer failure. Figure [sustainedIntp]presents a sustained interruption due to the operation of anupline circuit breaker. These disturbances are often permanentand require human intervention for system restoration [6].[float Figure:[float Figure:[Sub-Figure a:

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[Figure 1. 4:(a) Ovevoltage due to transformer failure (b) SustainedInterruption due to mulfunction of equipment.

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1. 1. 2 HarmonicsAccording to the IEEE definition harmonics are sinusoidalvoltages or currents having frequencies that are integermultiples of the frequency at which the supply system is designedto operate (termed the fundamental frequency; usually 50 Hz or 60Hz). Both the voltage and current harmonics are measured in terms oftotal harmonic distortion (THD) at the PCC, which is the pointwhere other customers can be connected with

the electric utility. And the quoted values are explicitly specified as voltage andcurrent values. Conventionally, current distortion measurementsare suffixed with ‘ I’, e. g. 30 % THDI, and voltage distortionsuffixed with ‘ V’, e. g. 5 % THDV. Figure 7 shows a fundamentalsinewave with 60% 3rd and 40% 5th harmonics.[float Figure:

[Figure 1. 5: Fundamental with 3rd and 5th harmonics.

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When talking about harmonics in power installations it is thecurrent harmonics that are of more concern because the harmonicsoriginate as currents and most of these waveform distortions aredue to these currents [8. 1]. Because of which striker limits areimposed by electrical utilities [7] . When harmonics currents fromthe different sources produce a drop across the impedancenetwork; they distort the voltage at that point. Another harmonicphenomenon is due to the shunt or series resonance in the networkthat can cause a voltage magnification [8]. But the most important reason that is also a concern for thefuture electrical utility is the way the loads draw current fromthe utility, which introduces harmonics in the system these arenon-linear loads. Figure [nonlinear loads] shows the currentdrawn by different non-linear loads. These currents result indistorted voltages that further affect the other loads in thesystem. As the number of harmonic producing loads has increasedover the years, it has become increasingly necessary to addresstheir influence when making any additions or changes to aninstallation [9].[float Figure: Harmonic currents of different non-linear loads.

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Normally the power system distribution is able to absorb theharmonic produced by the loads that satisfy the IEEE Std 519-1992limits at the PCC [10]. But it is the combined effect of manyloads at the PCC that could cause the harmonic distortion of mainsupply voltage, which can lead to energy losses due to unwantedcurrent in the system. As clearly visible in the Figure 7 and 8, the sum of the fundamental, 3rd and 5th harmonic that gives highpeaks that are phase dependent, which may result in defectiveoperation of regulating devices, malfunction of protective relaysor circuit breaker and other control systems. High harmonicsamplitude may also overload the power distribution network thusreducing its power transfer capability and overheat the neutralconductor because of skin and proximity effects, which increasewith frequency and dielectric breakdown may occur causing it toburn out [11- 13]. 1. 1. 3 Voltage UnbalanceIn simple terms, voltage unbalance is a voltage variation in apower system in which the voltage magnitudes are not equal or thephase angle differences between them is not 120 degree. Inreality this is impossible to achieve in a power system. Before going into any formal definition of unbalance system wefirst have to know how to quantify an unbalance voltage orcurrent in a three-phase system. This is done by mathematicallybreaking down the unbalance system in to three symmetricalbalanced. That are the positive-sequence, negative-sequence andzero-sequence components indicated by subscripts 1, 2, 0respectively, shown in the Figure [unbalance]. They arecalculated using matrix transformations of the three-phasevoltage or current phasors.egin{bmatrix}U_{0}U_{1}U_{2}end{bmatrix}= frac{1}{3}egin{bmatrix}1 & 1 & 11 & a^{2} & a1 & a & a^{2}end{bmatrix}egin{bmatrix}U_{a}U_{b}U_{c}end{bmatrix}Where the rotation operator a is given by: a= e^{j120^{o}}

- [float Figure: [Figure 1. 7: Positive, negative and zero sequence components

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For a perfectly balanced system both negative and zero sequencesystems would be absent. These sequence systems can be given somephysical interpretation. The direction of rotation of athree-phase induction motor when applied with a negative sequenceset of voltages is opposite to what is obtained when the positivesequence voltages are applied. Having no phase displacementbetween the three voltages in the zero sequence system, whenapplied to a three-phase induction motor, it will not rotate atall as there will be no rotating magnetic field. According to the IEEE definition of voltage unbalance its definedas the ratio of the negative or zero sequence component to thepositive sequence component. This is also known as negative sequence unbalance factor (NSUF). And it is considered to give the true unbalance in the system.\\%, NSUF= frac{U_{2}}{U_{1}}*100Where U_{1}and U_{2}are positive and negative sequencecomponents of three-phase line voltages can be calculated usingequation above. According to The

National Electrical Manufacturers Association(NEMA) the voltage unbalance is as follows: VoltageUnbalance:= frac{Maximum, deviation, from, the, mean, of, left{ Uab, Ubc, Uca ight} }{Mean, of,{U_{ab}, U_{bc}, U_{ca}}}Line-neutral voltages should not be used with equations (1) and(2) as the zero sequence components can give incorrect results. Although both definition give different result but the analysisin [17] shows that its not significant uptill 5% voltageunbalance. The main cause of voltage unbalance is the lack of symmetry inthe loads at the LV distribution network. Due to largesingle-phase loads like arc furnaces and welders connected at thedistribution network that makes the system unbalance. Also due tothe rapidly increase in the small distributed generations like PVpanels that are connected to low voltage distribution networkthrough a single phase power electronics converter. These smallgenerations have high impedance and low short circuit power thatresult in a large unbalance voltages. More over faulty powerfactor correction capacitor banks, and open delta or wyetransformers also contribute to unbalance voltage. Abnormalsystem conditions that typically include phase-to-ground, phase-to-phase and open conductor faults also cause phaseunbalance. The most common victim of unbalanced voltages is the electricmotor that happens to be the work horse of the modern industry. Unbalance voltage in an induction motor will reduce itsefficiency and cause heating in the windings that will reduce thelife of insulation and hence the motor life [21]. Even the NEMApremium efficiency motors are built for voltage unbalance of 1%[20]. Furthermore it also decreases the capacity of the cables andtransformer in power system due to negative sequence. In case oftransformer if the delta configuration is used the zero sequencewill circulate and cause heating [18]. AC variable speed drivesand converters normally draw non-linear current that injectsharmonics in to supply due to the unbalance voltage theseharmonics increases because the current becomes more non-linear[19]. 1. 1. 4 TransientsIn IEEE Std 100-1992 another synonymous used for transients issurge. It is defined as " a transient wave of current, potential, or power in an electric circuit." Based on the wave shape of thetransient current or voltage the transients can be classifiedinto two main categories, impulsive and oscillatory transients. Impulsive Transient is one of the two types of transientdisturbance that may enter the power system. It is defined byIEEE as a sudden, non–power frequency change in the steady-statecondition of voltage, current, or both that is unidirectional inpolarity – either primarily positive or negative. It is normally a single, very high impulse like lightning. Currents produced from a lightning strike can go to severalthousand amps in about 2-3us. Impulsive transients are generallydescribed by their rise and decay times. They can also becharacterized by their spectral content. Impulsive transients arenot usually transmitted far from the source of where they enterthe power system. However, in some cases, they may propagate forsome distance along distribution utility lines. Also, it mayconsiderably have different characteristics when viewed fromdifferent parts of the electrical system. In addition, the highfrequencies involved allow damping of the impulsive transientsthrough the resistive component of the system. Electrostatic Discharge is another form of an impulsivetransient. Most of us are familiar with this, since we may havealready experienced such when touching an object like door knobor another person, after walking across a carpeted floor.

Thesudden release of charge can damage sensitive electronics. Thisis the main reason why technicians use wrist straps whenservicing electronic equipment. The effects of transients on a power system depend on theamplitude of the transient and its frequency. In the case ofimpulsive transients, its amplitude is the main cause ofproblems. The damage caused by a transient can be immediate (i. e. lightning strike). It can also be gradual as in the case oflow-amplitude transients, which slowly degrade equipmentinsulation making it prone to short circuit [22]. Oscillatory Transient is described as a sudden, non–powerfrequency change in the steady-state condition of voltage, current, or both that has both positive and negative polarityvalues (bidirectional). In other words, the instantaneous voltage or current value of anoscillatory transient varies its polarity quickly. It isdescribed by its spectral content or predominant frequency, magnitude and duration. The oscillatory transient is subdividedinto three classes. These are based on selected frequency ranges, which correspond with common types of power system oscillatorytransient phenomena. It should also be noted that the frequencyof the oscillation gives a trace to the origin of the disturbance[25]. According to the classification given in IEEE Standard 1159-1995, an oscillatory transient with a primary frequency component lessthan 5 kHz, and duration from 0. 3 ms to 50 ms, is considered alow frequency transient [27]. These transients are normallyencountered on subtransmission and distribution systems thatcould originate primarily due to capacitor bank energization. Electric distribution utilities use capacitor banks to improvepower factor, as well as lower system losses. For better results, capacitor banks have to be switched in and out of the system tomatch with changes in the load profile. However, capacitor bankenergization yields an oscillatory voltage transient withfrequencies between 300 and 900 Hz [23-24], Figure shows thiseffect. Also, oscillatory transients with fundamental frequencies lessthan 300 Hz can be observed on the distribution system due totransformer energization and ferroresonance. In addition, seriescapacitors may also produce this transient type when the systemresonance causes the magnification of low frequency components inthe transformer inrush current or when unusual conditions lead toferroresonance. An oscillatory transient with a predominant frequency componentbetween 5 and 500 kHz and a duration measured in tens ofmicroseconds is termed a medium frequency transient. Back-to-backcapacitor switching is a typical example of these transients[26]. It occurs when a capacitor bank is switch in closeelectrical proximity to another capacitor bank that is alreadyenergized, which sees the de energized bank as a low impedancepath. Other causes of this type of transient includes cableswitching and as a system response to an impulsive transient. Oscillatory transients with a predominant frequency componentgreater than 500 kHz and a typical duration in microseconds areconsidered high frequency transients. This type of transients arelinked with power electronics and switching events such as lineor cable energization. Power electronics, like the SMPS incomputers, generate oscillatory voltage transients that repeatseveral times the system frequency. Usually, they are also theresult of a local system response to an impulsive transient. 1. 1. 5 Voltage Flickers[float Figure:[float Figure:[Sub-Figure a:

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[Figure 1. 8:(a)Voltage flicker due to an arc furnace and (b) transient due tocapacitor switching.

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A random or repetitive variation in the RMS voltage between 0. 9pu and 1. 1 pu, which cause rapid visible changes of light levelin lighting equipment is known as flicker. The term flicker isderived from the impact of the voltage fluctuation on lightingintensity. Voltage flicker can be separated into two types: cyclic and noncyclic. Cyclic flicker is a result of periodicvoltage fluctuations in the system voltage, with noncyclicreferring to occasional voltage fluctuations. The main cause of voltage changes is the time variability of thereactive power component of fluctuating loads. In general, voltage flicker occurs on relatively weak systems with a lowshort-circuit capacity. So the loads with a high rate of changeof line current in a short time can result in a flicker [28]. Arcfurnaces are the most common cause of voltage fluctuations on thetransmission and distribution system, see Figure [flicker]. Alsonote that small power loads such as starting of induction motors, welders, boilers, pumps and compressors, cranes, elevators etc. can also be the sources of flicker [28. 1]. Capacitor switchingand on-load transformer tap changers that can change theinductive component of the source impedance are also a cause offlickers [34]. Variations in generation capacity like, in windturbines can also have an effect. In some cases, voltagefluctuations can be caused by low frequency voltageinter-harmonics [33]. Voltage fluctuations have an effect on wide range of equipmentand devices that are commonly used in industry. In an inductionmotor these fluctuations can cause changes in torque and slip andin a worst case scenario that may lead to excessive vibrationsthat will reduce the mechanical strength of the motor [31]. Inphase-controlled rectifiers with dc-side parameter controlusually it is a reduction of power factor and the generation ofnon-characteristic harmonics and inter-harmonics. In an inverterduring drive braking commutation failure could occur due toflickers [32]. In order to protect equipment from unexpectedfailures and damages the voltage fluctuation measurements arerequired to determine actual load emission levels for comparisonwith limit values given in [29-30]. 1. 2 Mitigation of Power Quality IssuesFor the mitigation of the power quality issues whether it’s thecustomer or the power utility the economic factor is veryimportant. Most often no one is interested in investing until thepower quality issue becomes serious. In order to save hugeinvestment latter the best solution is to manage power qualityfrom the very beginning at the equipment level rather than at thePCC. For mitigation of PQ issues custom power devices are used. Thesedevices include both the passive and power electronics devicesthat are able to react in real time to the state of thedistribution system and adjusting itself to maintain the requiredlevel of power quality. The decision to choose between differentcustom power controllers is based on particular PQ issue, size ofsensitive load, geographic location and the condition of theelectrical network based on this data a cost analysis is done tofind the most suitable solution. Nowadays due to more sensitivenature of loads use of custom power devices that are electronicsbased to maintain power quality has become essential. The keytechnology that has made custom power devices possible is thesolid-state switch like the gate turn-off thyristor (GTO), theinsulated gate bipolar transistor (IGBT), and the integrated gatecommutated thyristor (IGCT). These devices have the operationalcapabilities suitable for high power applications at a cost thatmakes them economically possible for distribution power levels. In this section the passive and power electronic based custompower devices for voltage sags that are regarded as one of themost harmful power quality (PQ) disturbances due to their costlyimpact on industrial processes, harmonics that are rapidlyincreasing due to the use of non-linear loads and the voltageunbalance that affects the electric motor that is the work horseof the modern industry are discussed. 1. 2. 1 Passive Mitigation DevicesIn the following section, the passive custom power for voltagedip, harmonics and unbalance mitigation as shown in Figure [passiveMit], are discussed briefly: [float Figure: Passive mitigation devices for voltage sag, harmonics andunbalance.

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1. 2. 1. 1 Voltage Dip MitigationFerro- resonant TransformerThe purpose of the Ferro-resonant transformer is to provideconstant output voltage despite of changing in input voltage andload. Sometimes these transformers are also

called as Ferros orCVTS (constant voltage transformers) [37]. In actual design ofthis transformer as shown in Figure [FRTa] the capacitor isconnected to the secondary winding of the transformer to set theoperating point above the knee of the saturation curve, Figure [FRTb]. These kinds of transformers are only used for low-power; constant loads because variable loads can cause problems, due tothe presence of tuned circuit on the output.

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[Figure 1. 10:(a) Single line diagram of Ferro-resonant transformer and (b) thesaturation curve of transformer.

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Static Var Regulator (SVR)The first static tap-changer in the world was used in the fieldoperation in Norway in 1986 by ABB components [38]. It is used toavoid voltage sag. In this kind of the transformer thyristorbased tape changer can be mounted on its secondary winding forthe sensitive loads to change its turn ratio according tovariations in the input voltage [39]. The Figure [SVR] shows thediagram of transformer with electronic tap-changer.

[float Figure: [Figure 1. 11: Single line diagram of Transformer with electronic tap-changer.

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The secondary winding feeds the load and its voltage regulationis accomplished by connecting and disconnecting differentsections of the same winding by fast static switches in thesteps. This fast switching of winding sections also results intransients because of change in winding inductance which is thedrawback of this technique. Also note that this techniqueinvolves static switches so it can also be put in powerelectronics based voltage sag mitigation devices. Rotating machines (Motor-Generator set)Motor-Generator set consists of motor supplied by grid, asynchronous generator supplying the load and the flywheel; allare connected at a common axis. Three-phase diagram ofmotor-Generator set with flywheel is shown in Figure [MGset]. When motor rotates the rotational energy will be stored in theflywheel which is used to maintain voltage regulation duringdisturbances. This scheme has high efficiency and low initialcost but it can only be used in industrial environment due itssize, noise and maintenance requirements.[float Figure: [Figure 1. 12: Three phase diagram of Motor-Generator set with flywheel.

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1. 2. 1. 2 Harmonic mitigationPhase Shifting TransformerPhase shifting transformers are the effective way to cancel outthe 5th and 7th harmonic. This method is clear and fundamentallyeasy to understand. The principal is

to take harmonics generatedfrom separate sources, shift one source of harmonics 180° withrespect to the other and then combine them together; this willresult in cancellation. When load currents are not matched, theharmonics can be partially cancelled. It may be a singletransformer with two separate windings (ie: delta and wye) asshown in Figure [PshiftingTran].

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(a) Three phase diagram of Dyd transformer and (b) single linediagram of tuned filter.

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Tuned Harmonic filterThese harmonic filters are used to reduce the harmonic distortionin the supply system. A tuned harmonic filter is a device withtwo basic elements an inductor and a capacitor. These reactiveelements are connected in series to form a tuned LC circuit. Thetuned harmonic filter is connected as a shunt device to the powersystem as shown in the Figure [Tuned filter] below. The tuned harmonic filter is a resonant circuit at the tuningfrequency so its impedance is very low for the tuned harmonic. Because of the low impedance at the tuned harmonic frequency thetuned filter now becomes the source of the tuned frequencyharmonic energy demanded by the loads, rather than the utility. The filter impedance at the tuning harmonic behavior is like aresistor; below the tuning frequency it has a capacitivebehavior, while the impedance above the tuning frequency has aninductive behavior. Due to the capacitive behavior at below thetuning frequency, the filter improves the displacement powerfactor. At the tuning frequency the filter acts like a very lowresistance, and a great amount of harmonic current at thisfrequency flows through the filter and the total harmonic currentdistortion in the upstream system decreases. And the harmoniccurrents flow between the filter and loads. This decrease in thetotal harmonic current distortion improves the distortion powerfactor and thus the total power factor [35]. Low Pass FilterLow pass harmonic filters are popular due to their ability toattenuate all harmonic frequencies and achieving low levels ofresidual harmonic distortion. There are several circuitconfigurations available for the low pass filters. Typically, lowpass filter configuration includes one or more series elementsplus a set of tuned shunt elements as shown in Figure [LPF].[float Figure:[Figure 1. 14: Single line diagram of Low pass filter.

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There are three parts input side, the shunt part and output theload side. The purpose of input stage is to isolate the LPF fromother harmonics sources connected to the same power source and toprevent power system resonance. This stage also protects the loadand filter capacitors against transients. The output stagecontains a precise amount of impedance that minimizes the amountof harmonics produced by the load. It also reduces the harmonicburden placed on the shunt stage, and prevents resonance betweenthe shunt stage and the load. The shunt stage absorbs residualharmonics remaining after both the input and output stages haveplayed their roles in reducing load harmonics (primarily 5th and7th). Our basic three stage filter design achieves the lowestpossible harmonic distortion levels while preventing power systemresonance. The low pass filter forms a hybrid combination ofseries and shunt elements that can be applied without performingsystem harmonic analysis. IGBT Based fast switching harmonics filterThis harmonic mitigation technique is useful in situationsinvolving dynamic loads with rapidly changing demands forreactive power. These filters are switched very rapidly IN andOUT of the circuit using IGBT’s instead of contactors. This typeof filter is also capable of soft switching the capacitorssuppressing voltage spike. It can be switched, withoutdischarging the capacitors, at switching rates up to 60 times persecond. The main advantages of this filter are the capability toswitch without transients and to respond in real time, todynamically changing load conditions. The performance of the fastswitched filter is similar to the performance that can beexpected from a typical tuned filter, a total harmonic currentdistortion from 3 to 12% [35]. 1. 2. 1. 3 Unbalance MitigationScott-transformerThis transformer transforms three phase power to two-phase power. It consists of two single phase transformer with a specialwinding ratio. One of the two single phase transformers has amiddle-tapped winding on its primary side, and a single windingon its secondary side. Figure shows the scott connection scheme. They are connected in such a way that at the output, a two-phaseorthogonal voltage system is generated allowing the connection oftwo single-phase systems. This setup draws a balanced three-phasepower from the grid.[float Figure:[float Figure:[Sub-Figure a:

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[Figure 1. 15:(a) Schematic diagram of scott-transformer and (b) the singleline diagram of steinmetz transformer for induction furnace.

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Steinmetz-transformerIt is a three-phase transformer with an extra power balancingload, consisting of a capacitor and an inductor that are ratedproportional to the single phase load, Figure shows the steinmetztransformer for load balancing in a large induction furnace load. When the reactive power rating of both the inductor and thecapacitor is equal to the active power rating of the load(divided by root 3) then the three-phase grid sees a balancedload. The three-phase rated power of the transformer is equal tothe single-phase active power of the load. This balancing is onlyperfect for loads with an active power equal to the value used todesign the system. The detail calculation using steinmetztransformer can be found in [36]. 1. 2. 2 Power Electronics based mitigation devicesAt the heart of the custom power devices that are powerelectronics is a three-phase voltage source inverter. Theinverter is controlled by a digital system that constantlymonitors the distribution line and controllers the outputaccording to some control algorithm. The inverter is connected tothe distribution line via a filter that removes the harmonicsinjected by the inverter and a transformer for isolation. Theinverter itself could be a 2 level PWM or multi-level inverter. The custom power devices that can inject active power need anenergy storage that could be capacitors, batteries, flywheel orsuperconducting magnetic energy storage (SMES). Table [ActiveDevices]shows some of the power electronic based custom power devicesfor mitigating voltage dips, interruptions, harmonics, unbalanceand flicker. These devices are briefly discussed in the followingsection.[float Table:[Table 1. 1: Summary of mitigation capability of various power electronicsbased custom power devices.

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Devices	Voltage Dip	Interruption	Harmonics	Voltage Unbalance	Flicker
STS	x	x			

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| DVR | x | | | x | x |

+------------+--------------+---------------+------------
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| SVC | | | x | x | x |

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| UPS | x | x | x | x | x |

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| D-STATCOM | x* | x* | x | x | x |

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[footnote:* Only if energy storage is present.

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1. 2. 2. 1 Static Transfer Switch (STS)The static transfer switch (STS) is an electrical device whichallows the instantaneous transfer of the load from preferredsource to an alternative healthy source in case of the voltagedisturbance. This means that if one power source fails STSswitches to the back-up power source quickly in such a way thatload never realizes any disturbance. Figure [STS]shows singleline diagram of Static Transfer Switch (STS).[float Figure:[Figure 1. 16: Single line diagram of STS.

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Normally, static switch on the primary source is fired regularly, while the other one is off. It is generally used to mitigatevoltage sags and interruptions in the distribution system but itcannot protect against the sag originating in the transmissionsystem. 1. 2. 2. 2 Uninterruptible Power Supply (UPS)The main purpose of uninterruptible power is to provideuninterruptible, reliable, and high quality power to the loads. UPS consists of rectifier which is supplied by grid, battery andthe inverter which supplies the load. Figure [UPS] showsthree-phase diagram of UPS. The rectifier is used to convert acvoltage into dc which supplies power to the inverter as well asbattery bank to keep it charged. In normal operating conditions, battery gets charged and power is supplied to the inverter byrectifier. In case of an outage, battery bank supplies the powerto the load [40]. Depending upon the storage capacity of thebattery, it can supply the load for minutes or even hours. UPS isa low power application device and is used in medical equipment, data storage and computer system, emergency equipment, telecommunications and online management systems [41]. Forhigher-power loads the costs associated with losses due to thetwo conversions and maintenance of the batteries become too highand, therefore, a three-phase, high power UPS is not economicallyfeasible.[float Figure:[Figure 1. 17: Three phase diagram of UPS.

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1. 2. 2. 3 Shunt connected Voltage source Converter (D-STATCOM)The Distribution Static Compensator (D-STATCOM) is a shuntconnected voltage source converter based static compensator whichis used for voltage regulation at the PCC and reactive powercontrol by injecting controlled amount of current underline{i}_{r}(t)of desired amplitude, frequency and phase into the grid. Thetypical configuration of a STATCOM is shown in Figure [Dstatcom1]. This device consists of a VSC, an injection transformer, an ACfilter and a DC-link capacitor. The line impedance has aresistance R_{g}and inductance L_{g}. The grid voltage andcurrent are denoted by underline{e}_{s}(t)and underline{i}_{g}(t), respectively. The voltage at the PCC, which is also equal tothe load voltage, is denoted by underline{e}_{g}(t)and theload current by underline{i}_{l}(t). The inductance andresistance of the AC filter reactor are denoted by R_{r}and L_{r}, respectively.[float Figure:[Figure 1. 18: Single line diagram of shunt connected VSC.

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By injecting a controllable current, a STATCOM can limit voltagefluctuation leading to flicker [42] and cancel harmonic currentsabsorbed by the load, thus operating as an active filter [43]. Inboth cases, the principle is to inject a current with sameamplitude and opposite phase as the undesired components in theload current, so that they are cancelled in the grid current. These mitigation actions can be accomplished by only injectingreactive power.[float Figure:[Figure 1. 19: Phasor diagram of D-STATCOM

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A STATCOM can also be used for voltage dip mitigation if energystorage can also be mounted on the DC link to allow active powerinjection into the AC grid. In this case, the device has toinject a current in the grid which results in an increasedvoltage amplitude at the PCC, as shown in the phasor diagram inFigure [Dstatcom2]. The voltage phasor at PCC is denoted by overline{E}_{g}, overline{Z}_{g}is the line impedance, overline{E}_{s, dip}is the grid voltage phasor during the dip and psiis thephase-angle jump of the dip. From the diagram it is possible to understand that when theshunt-connected VSC is used to mitigate voltage dips, it isnecessary to provide energy storage for injection of active powerin order to avoid phase-angle jumps of the load voltage. If onlyreactive power is injected, it is possible to maintain the loadvoltage amplitude E_{g}to the pre-fault conditions but not itsphase [41. 1]. Therefore, the voltage dip mitigation capability ofa shunt-connected VSC depends on the rating of the energy storageand on the rating in current of the VSC. One drawback of usingD-STATCOM for voltage dip mitigation is a high rating of voltagesource converter. To restore the load voltage to the pre-faultconditions (without introducing phase-jump), the followingcondition must be fulfilledoverline{E}_{g}= overline{E}_{s, dip} +overline{Z}_{g}overline{I}_{r}Active and the reactive power injected by the device can becalculated in per unit asP_{inj}= frac{cosvarphi}{Z_{l}}-frac{E_{s}(E_{s, dip}cos(varphi_{g}-varphi_{s})-cos(varphi_{g}-varphi_{s} +psi))}{E_{s, dip}Z_{g}}Q_{inj}=-frac{sinvarphi_{l}}{Z_{l}}+frac{E_{s} (E_{s, dip}cos(varphi_{g}-varphi_{s})-sin(varphi_{g}-varphi_{s}+psi))}

{E_{s, dip}Z_{g}}where the souce voltage, the line impedence and the loadimpedance are expressed as overline{E}_{s}= E_{s}e^{jvarphi_{s}}, overline{Z}_{l}= Z_{l}e^{jvarphi_{l}}and overline{Z}_{g}= Z_{g}e^{jvarphi_{g}}, respectively. 1. 2. 2. 4 Dynamic Voltage Restorer (DVR)Dynamic Voltage restorer (DVR) is series connected voltage sourceconverter based compensator which is used to inject voltage underline{e}_{c}(t)of controllable amplitude and phase angle between the PCC andthe load in series with the grid voltage through injectiontransformer to compensate for voltage dips. It is connected inseries with a distribution feeder and is used to generate orabsorb active and reactive power at its ac terminals. The firstDVR was installed for rug manufacturing industry in NorthCarolina [44]. Another was used in Australia for large dairy foodprocessing plant [44]. Figures [DVR1] and [DVR2] show the singleline and simplified diagram of the Dynamic voltage restorerrespectively. It is used to maintain load voltage underline{e}_{l}(t)to the pre-fault condition by injecting missing voltage ofappropriate amplitude and phase.[float Figure: [Figure 1. 20: Single line Diagram of DVR.

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[float Figure: [Figure 1. 21: Simplefied diagram of DVR.

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[float Figure: [Figure 1. 22: Phasor diagram of DVR during voltage sag mitigation.

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Figure [DVR3] shows the phasor diagram of series injectionprinciple during voltage dip mitigation, overline{E}_{l}is thephasor of pre-fault load voltage, overline{E_{c}}is the phasorof injected voltage by the device, overline{I_{l}}is thephasor of load current, varphiis the phase displacement fromthe load current and load voltage, overline{E}_{g, dip}is thedip in the amplitude of the grid voltage and psiis phase anglejump. The DVR injects reactive power for compensation of voltageamplitude but it injects active power for correcting phase anglejump as well. Injection of active power by DVR is related toenergy storage. DVR injecting larger amount of active powerrequires bigger size of energy storage leading to more expensivescheme rather than injecting less amount of active power. Thesize of energy storage can be reduced by optimization of energystorage by using the techniques in [45]. Assuming the loadvoltage and current in pre-fault conditions is equal to 1 pu, theinjected power by the device during voltage dip mitigation isequal tooverline{S}_{inj}= overline{E}_{c}overline{I}_{l}^{*}=(overline{E}_{l}-overline{E}_{g, dip})overline{I}_{l}^{*}=(1-E_{g, dip}e^{jpsi})e^{jvarphi}The euler identity can be written as e^{jvarphi}= cosvarphi+jsinvarphi, applying to equation 2. 2 we getoverline{S}_{inj}= cosvarphi+jsinvarphi-E_{g, dip}cos(varphi+psi)-jE_{g, dip}sin(varphi+psi)overline{S}_{inj}=(cosvarphi-(E_{g, dip}cos(varphi+psi))+j(sinvarphi-E_{g, dip}sin(varphi+psi))Power absorbed by the load will be given byoverline{S}_{load}= P_{load} +jQ_{load}= overline{E}_{l}overline{I}_{l}^{*}= e^{jvarphi}=

cosvarphi+jsinvarphiTherefore the active and reactive power injected by the DVR aregiven byP_{inj}=(1-frac{E_{g, dip}cos(varphi+psi)}{cosvarphi}P_{load}Q_{inj}=(1-frac{E_{g, dip}sin(varphi+psi)}{sinvarphi}Q_{load}The main components of DVR are: Voltage source converter (VSC) Generally pulse-width modulatedvoltage source converter is used because of simplicity and goodresponse. It is used to generate desired voltage to be injectedfor the compensation. The basic function of VSC is to convert DCvoltage supplied by the energy storage into AC voltage and viceversa so it can be said that it is a converter through whichpower flow is reversible. When power flow is from DC to AC itsaid to be in inverter mode and when power flow is from AC to DCit is in rectifier mode. The valves in converter are usuallyIGBTs, but some DVR manufacturers also use IGCTs [46-47]. Series Injection Transformer The main purpose of injectiontransformer is to increase the voltage supplied by LC filter andto inject the missing voltage of the system at the load bus. Forthree-phase DVR, three single-phase transformers are used forthis purpose [48]. The high voltage side of the transformer isconnected in series to the line, while DVR power circuit isconnected to the low voltage side. The primary winding can beconnected in either star or in delta with the converter side. When three single-phase converters are used, a connection ofthree windings of transformer will be in wye to realize afour-wire configuration in order to inject a zero-sequencevoltage into the line. A delta connection increases the injectedvoltage (in pu) with respect to the converter output voltage by afactor of √3 and have an advantage of blocking zero sequencecurrents that may circulate in the feeder. To operate theinjection transformer properly into the DVR, MVA rating, turnsratio, the primary winding voltage and current ratings and shortcircuit values of transformer are required [48]. Energy storage An energy storage device is normally connected tothe DC bus of the converter to provide the required energy forthe compensation. Commercially available DVRs use largecapacitors banks for the storage of energy [49]. This is the mostexpensive part of DVR . In normal operating condition it ischarged through grid voltage and in case of disturbance itsupplies energy to compensate for load voltage. Passive filter The nonlinear characteristics of semiconductordevices cause distorted wave forms associated with high frequencyharmonics at the output of the inverter. To reduce theseharmonics filter unit is used. Although PWM technique is used inthe converter with high switching frequency which generates avoltage wave form with very low content of the harmonics, asecond-order LC filter is used for further reduction of theharmonics in the injected voltage. 1. 2. 2. 5 Static var compensators (SVCs)The purpose of a compensator is to measure adequate electricquantities of the load and generate in the compensator suchcurrents, that the resultant load: compensator – compensatedload, as seen from the supply network, was symmetrical, and thefundamental harmonic reactive current drawn from the network didnot exceed the value permitted in the supply conditions. Generally, static compensators are the systems, which comprisereactors and/or capacitors controlled by means of semiconductorcircuits. Thyristor Controlled Reactor (TCR)The TCR operates as a gradually variable reactor, shown in Figure. It’s just a reactor connected in shunt through a thyristor thatcan be controlled by continuously changing the firing angle alpha, which changes the susceptance of the TCR, Figure shows the V-Icharacteristics of TCR. In the V-I plane, it means " jumping" fromone characteristic to the other – the whole range between alpha= 0and alpha= 90can be covered [6].[float Figure:[float Figure:[Sub-Figure a:

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[Figure 1. 23:(a) Single line diagram of TCR and (b) the characteristic curveof TCR.

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Fixed capacitor/thyristor controlled reactor (FC/TCR)The simplest way to realize continuous voltage regulation both ininductive and capacitive range is putting a capacitor in parallelwith a TCR known as FC-TCR as shown in Figure . When TCR is off, we have only FC and when TCR is fully on, half of its current istaken by fixed capacitor. The range of regulation is always 1 pu, but now we regulate both E> Vrefand E]

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[float Figure:[Sub-Figure b:

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[Figure 1. 24:(a) Single line diagram of FC/TCR and (b) the characteristiccurve of FC/TCR.

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FC/TCRs are employed where control requirements demand finerresolution that is not possible or economical with switchedcapacitor steps. For example, in applications where the shortcircuit ratio is low, very small compensation steps are needed toreduce flicker. A large number of small binary-switched capacitorsteps would be required, increasing the cost and complexity of asolution that only used a fixed capacitor array. The FC/TCRcombination can provide a more effective and lower cost solutionwhen finer resolution is necessary. Thyristor switched capacitor (TSC)The TSC is used to inject reactive power into the grid. Similarto the TCR, it is constituted by an AC switch connected in serieswith a fixed capacitor. A small inductor is needed to limit thedi/dt during switching operation. Using one TSC gives discretevariation of reactance with two operating points for each voltagevalue (TSC ON or OFF). Splitting the same total capacitance intomore TSCs gives more operating points and higher controllabilitybut increases cost. Also it is not possible to change thesusceptance continuously to realize constant voltage. When theTSC is started, a resistor in series with the capacitors canensure that they are charged slowly, thereby avoiding high inrushcurrents and system disturbances. After the capacitors areinitially charged, a contactor can automatically bypass theresistor.[float Figure:[float Figure:[Sub-Figure a:

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[Figure 1. 25:(a) Single line diagram of TSC and (b) the characteristic curveof TSC.

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Thyristor controlled reactor/thyristor switchedcapacitor(TCR/TSC)[float Figure:[Figure 1. 26: Characteristic curve of TCR/TSC.

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With a combined TCR/TSC compensator, continuously variablereactive power is obtained throughout the complete control rangeas well as full control of both the inductive and the capacitiveparts of the compensator. This is a very advantageous featurepermitting optimum performance during large disturbances in thepower system. Also with the capacitor able to switch on/off bythyristors (TSC) the same resulting characteristic can beobtained with half the size of the reactor. It’s a good solutionwhen the voltage variations around Vref are not big and when thesame regulation range is needed in both inductive and capacitiveregions. But the cost of the switches and the complexity of thealgorithm for transient-free switching of the capacitor are fewdrawbacks for this solution. 1. 3 Case StudiesThis section presents some case studies where custom powercontrollers were installed to mitigate a power quality problem. Each case study presents a problem and the solution chosen alongwith the results after the mitigation. 1. 3. 1 Case Study1: Voltage Flicker mitigation using D-Statcom atSeattle Iron & Metals Corporation steel recycling facility inSeattle. ProblemIn the year 1999 the Seattle Iron & Metals Corporation was a newsteel recycling facility in Seattle, Washington. They have a huge4000 hp shredder motor load that will be operating at this newfacility. The distribution company Seattle city light has twosubstations to supply the plant, the South Substation andDuwamish Substation at 26. 4 kV distribution network. But bothefeeders during the operation of the shredder motor gives voltageflicker at the PCC. The Figure shows the plant single linediagram with source impedance Z1, feeder impedance Z2 and thetransformer impedance Zt.[float Figure:[Figure 1. 27: System Configuration

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SolutionThe company provided the load fluctuation profile, shown infigure along with the flicker limitation as specified by IEEE std1250-1995. The shredder motor specifications along with the maxtorque limit of the motor are also given in []. Only the voltagefluctuations caused by the shredder motor are considered in thisstudy. The PCC for evaluating the voltage fluctuation is on the4. 16 kV bus on the low voltage side of the system supplytransformer (5 MVA, 26. 4kV / 4. 116kV transformer), i. e., point Cin Figure 5. Most effective way is to mitigating the problem atthe source so that it doesn’t affect the other loads in thedistribution network. The measurement of voltage fluctuation ismade to detect the 4. 16kV bus through a PT, and the rms value ofline-to-line voltage of one phase is measured with a voltagetransducer, which can be seen in Figure 8.[float Table:[Table 1. 2: Load Fluctuation Profile and Flicker Limit

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No	Load Condition	Load Current	Fluctuation Frequency	Upper Limit of riangle V
1	200% load	2*FLA	1 hit/hour	2. 7%
2	175% load	1. 75*FLA	10 hit/hour	1. 1%
3	150% load	1. 5*FLA	20 hit/hour	0. 9%

4	100% load	1*FLA	20 hit/hour	0. 9%
5	50% load	0. 5*FLA	1 hit/minute	0. 7%
6	25% load	0. 25*FLA	5 hit/minute	0. 5%

[footnote: FLA: Current at Load= 1 pu (= 450A)

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[float Figure:[Figure 1. 28: Mesurment System used

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[float Figure:[Figure 1. 29: Voltage fluctuation level at point C without compensation.

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After the measurement the voltage fluctuation with the feedersfrom both the substations, the supply from the south feederresulted in more voltage fluctuation then Duwamish feeder, theresults of the former are shown in figure[]. After considering theload fluctuation profile, the flicker limits shown in figure[]and the worst case voltage fluctuation that occurred when thesouth feeder was used, especially with the 200% FLA. The size ofthe D-Statcom is determined that is to be 5 MVA at 4. 16kV thatwill reduce the flicker level within the specified limit of 2. 7%on the secondary of transformer, Figure [] shows the plant withD-Statcom. The results obtained after the D-Statcom installed tocompensate the voltage flicker at the low voltage side oftransformer are very convincingly within the specified limits, Figure[] shows these results.[float Figure:[Figure 1. 30: Voltage fluctuation level at point C with compensation.

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[float Figure:[Figure 1. 31: System with D-Statcom installation at point C.

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1. 3. 2 Case Study 2: Voltage Sag mitigation using a 4MVA DVR atCaledonian paper's manufacturing plant in Ayrshire. ProblemCaledonian paper's manufacturing plant in Ayrshire is part of theUPM-Kymmene Group that is one of the largest manufacturers oflightweight coated (LWC) paper in the world. The supply to theplant is taken from the Scottish Power (a power utility company)132kV transmission system that has an inherent power qualityissue of voltage disturbances. The paper machine process requiresprecise control of the paper sheet tension as it progressesthrough

the machine. On Caledonian Paper’s paper machine this isachieved by controlling 23 separate DC variable speed drives, which are inherently vulnerable to voltage disturbances becauseof problems with the control of thyristor firing. Firing anglecontrol has difficulty following the voltage change, withpossible consequential damage to the thyristors. To prevent thisdamage, it is common for drives to be equipped with protectionthat trips the drive, using settings dependent on the drive’ssensitivity to voltage disturbances. The manufacturer designedthe software voltage trip threshold in the drives at 90%, so thatdisturbances below this level for more than a few cycles cause atrip. According to the monitoring carried out on Scottish Power’stransmission and distribution system, and also within the papermill, it was confirmed that the paper machine could be affectedby disturbances of only 10% variation from normal (90% voltageretained) and for as little as 100ms. So in case of a voltagedisturbance that results in the tripping of DC drive, the papermachine suddenly stops in an uncontrolled manner with thepotential for extensive damage particularly, in the wire andpress sections. In these sections the wires, rolls, associatedfelts and paper sheet all go out of control at high speed due tothe voltage disturbance and, apart from the immediateinterruption to production, the situation demands time-consumingclean up and inspection of equipment and machinery. If there isdamage, depending on the part and extent of the damage, it cantake several hours to restore production to original levels. Wasting valuable time and costing in both material and labor.[float Figure:[Figure 1. 32: Single line diagram of Caledonian paper's manufacturing Plant.

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SolutionOn ScottishPower’s transmission system, the best clearance timesfor protection and circuit breakers is 80-150ms, are not fastenough to prevent possible disturbances to paper machineproduction. However, the severity of any disturbance event issubject to the ‘ geography’ of the power system between the plantand the fault location. Since the plant has a connection from the132kV transmission system it is not exposed to the faultoccurring in the distribution level. Different possible solutionslike changing the tripping threshold of the drives that improvedthe drive resilience but did not provide a complete solution. Useof the UPS also not considered due to high load and short ridethrough requirement. Based on the size, cost and the suitabilityDVR became the preferred option. Next the DVR size need to beselected based on voltage disturbance statistics of the site, itsduration and depth, the total size of sensitive load in the plantand its sensitivity limit. After considering the above factorsthe mill distribution system need to be segregated into criticaland non-critical groups with critical load of 8. 2 MVA, shown inFigure . Thus the 4 MVA (2*2MVA units in parallel) DVR wereinstalled to provide 50% injection for a duration of 300msecusing 800kJ of capacitance as energy storage. Figure shows anevent recorded in an overhead line fault due to lighting and theDVR has retained voltage at the planned level of 95% voltageenabling the plant ride through of voltage sags. Table showsdifferent recorded compensations by DVR.[float Figure:[Figure 1. 33: Single line diagram of manufacturing plant after the DVRinstalation.

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[float Figure:[Figure 1. 34: An event mitigated by the installed DVR.

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[float Table:[Table 1. 3: Disturbances compensated by the DVR.

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Date	DVR input voltage retained (%)	DVR input dip duration (msec)	cause
03 Apr 98	89	320	11kV: neighbouring customer fault.

20 May 98	81	1600	33kV: lightning-double circuit overhead line fault.
01 Sep 98	83	115	275kV: lightning: ovehead line transient.
29 Nov 98	81	135	275kV: unkown ovehead line transient.
04 Jan 99	88	123	132kV: gales: overhead line transient.
04 Jan 99	89	84	132kV: gales: overhead line transient.

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1. 4 SummaryThe key power quality issues that have significant impact at thedistribution level such as voltage sag, interruption, voltageunbalance, harmonics, flickers and transients are discussed. Thecustom power devices that are used mitigate these issues bothpassive and power electronics based are briefly explained tohighlight the advantages and disadvantages. Then two case studiesof actualy projects are presented explaining the problem andfinally presenting the solution along with improved results aftermitigation of particular power quality issue.